Penman-Monteith Evapotranspiration Calculations: Reference ET and Crop Coefficients

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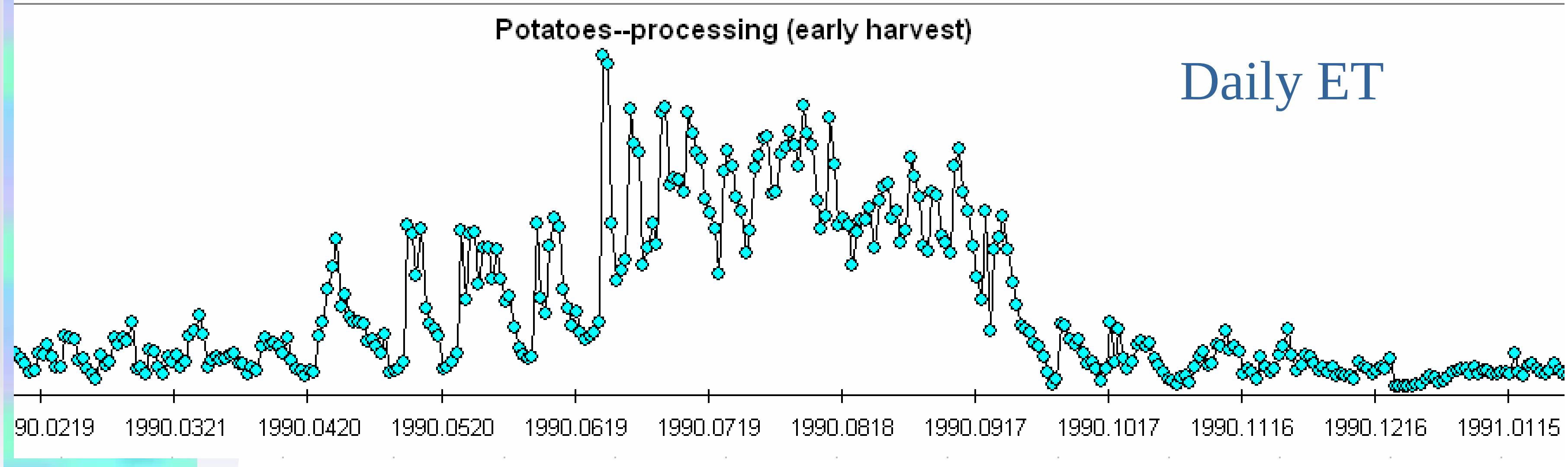
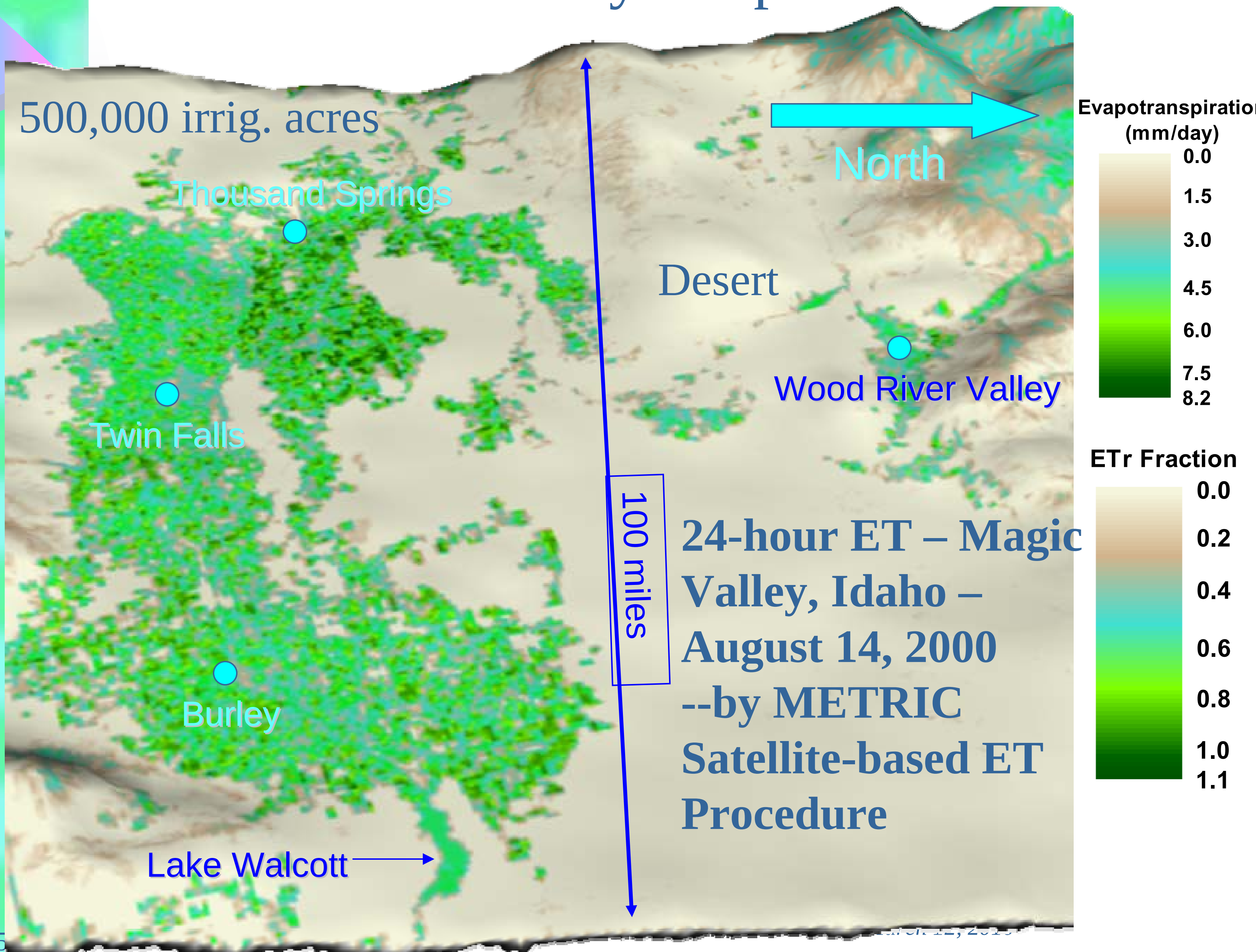
University of Idaho

Evapotranspiration (ET) varies widely with
- Time of Year
- From Day to Day

Ashton, 1990 calendar year -- Potatoes



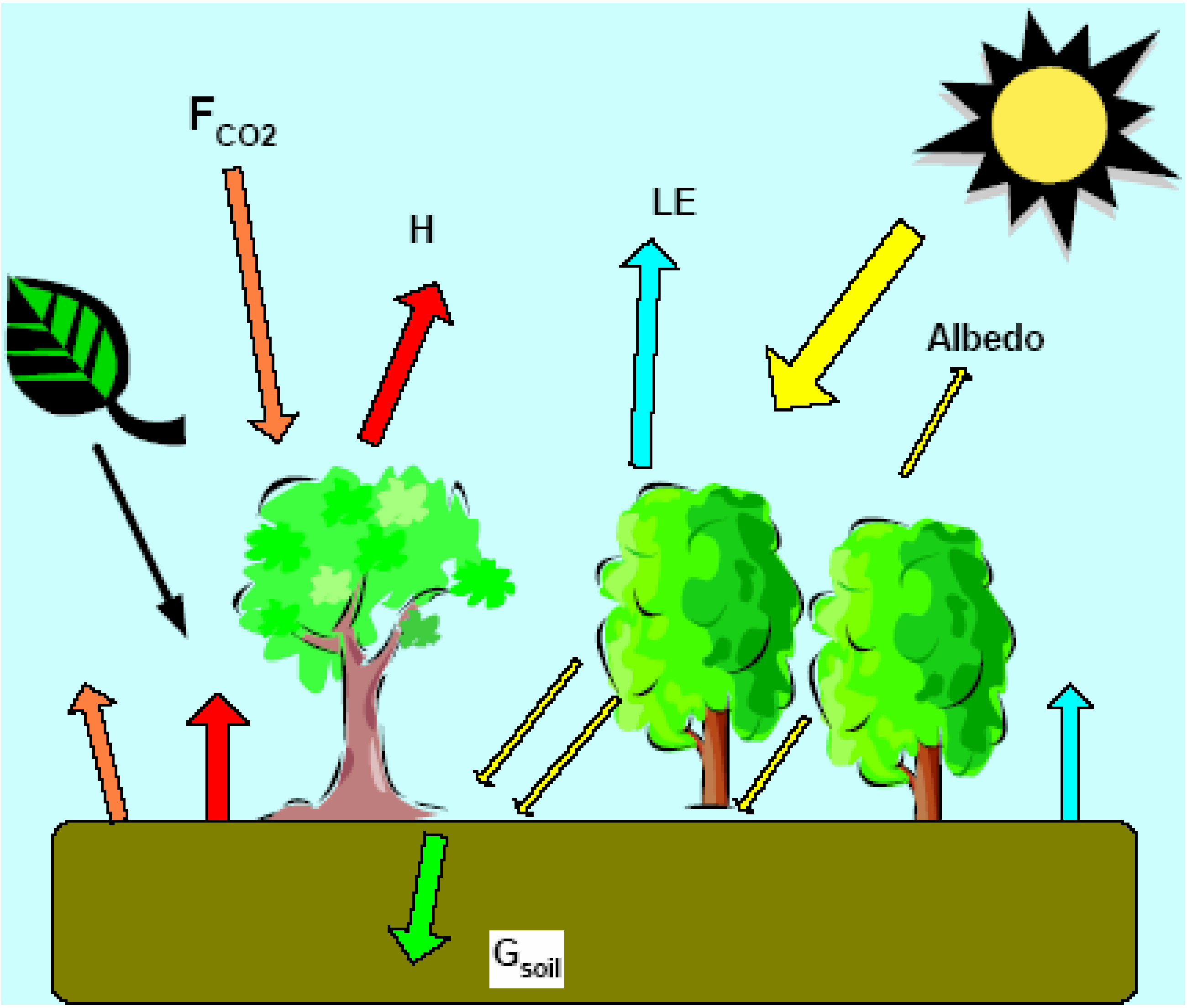
and ET varies widely in Space



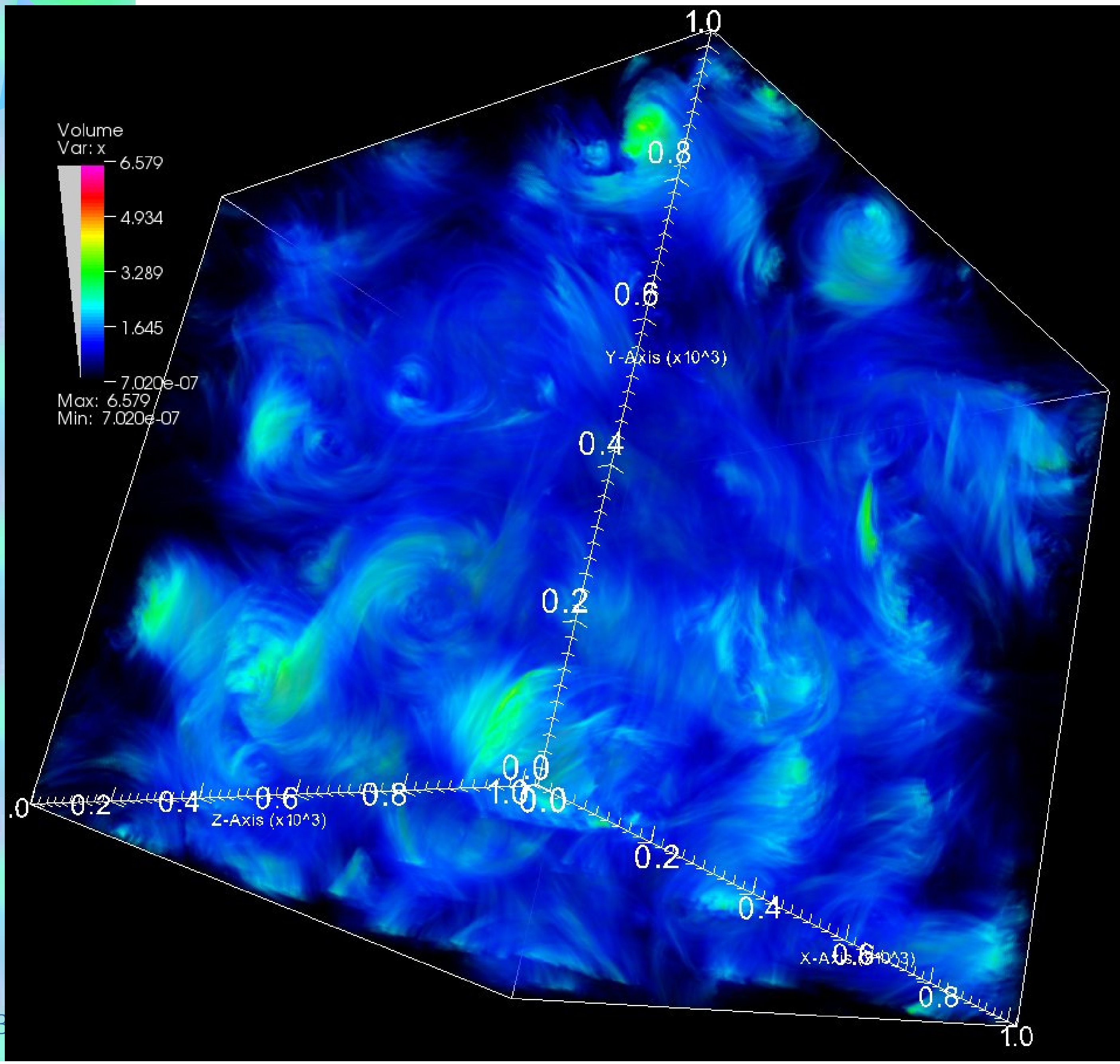
Brief Overview of the Penman-Monteith

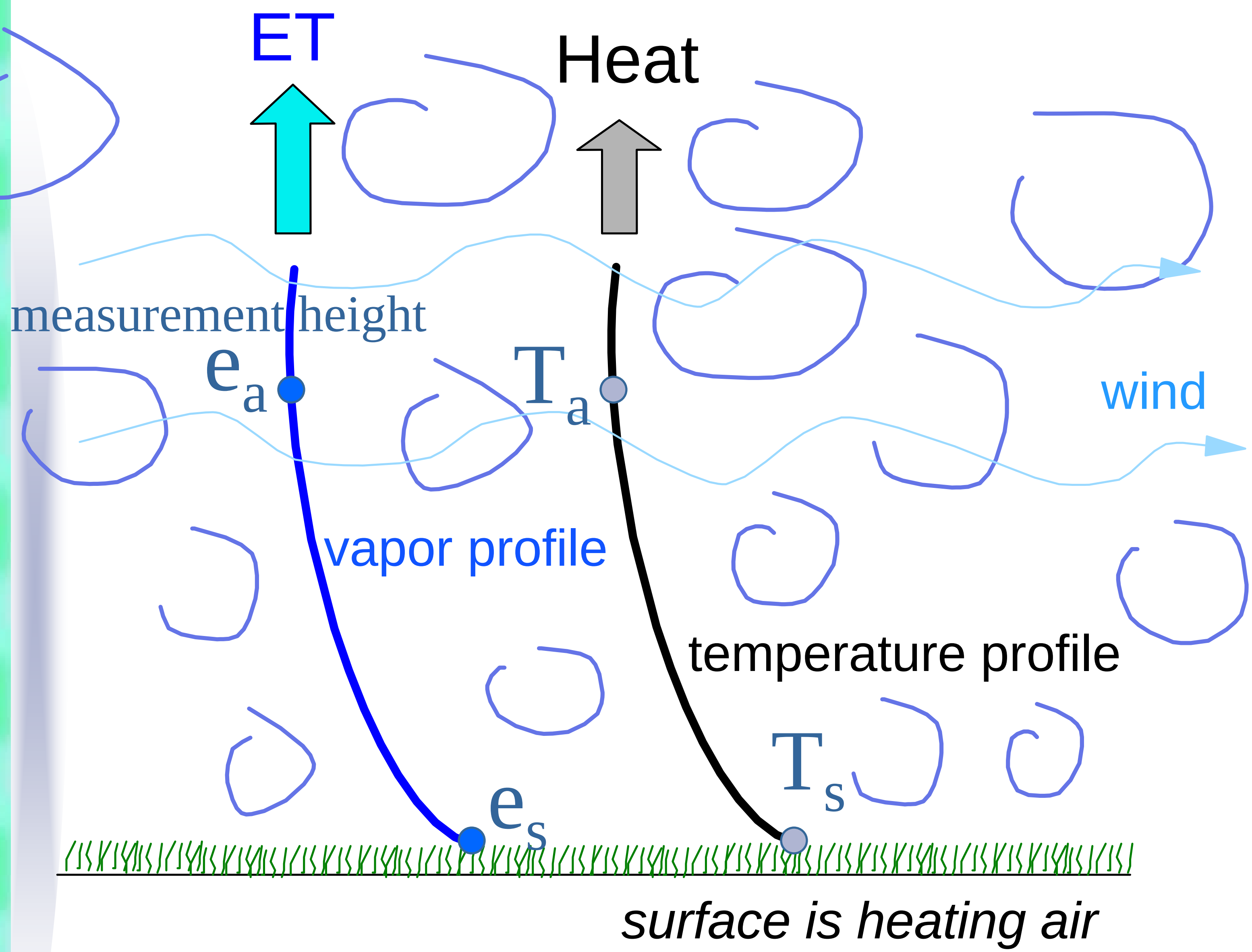
Combination of Energy Balance and Aerodynamic Transfer

ET is governed by Energy Availability and Aerodynamics

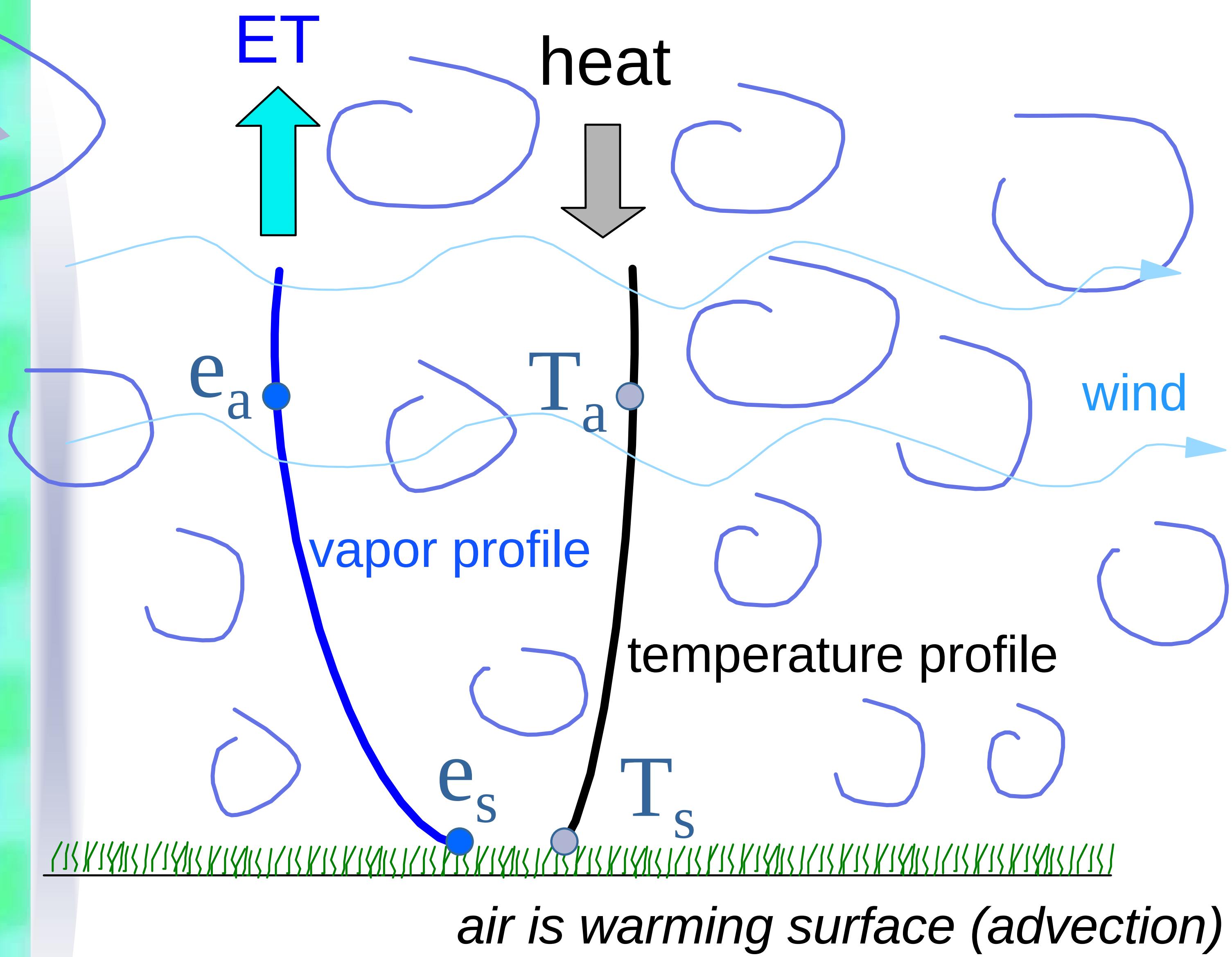


The lower atmosphere is turbulent, impacting Heat and Vapor Transfer





Aerodynamic Turbulence + Vapor and T Gradients → ET, H

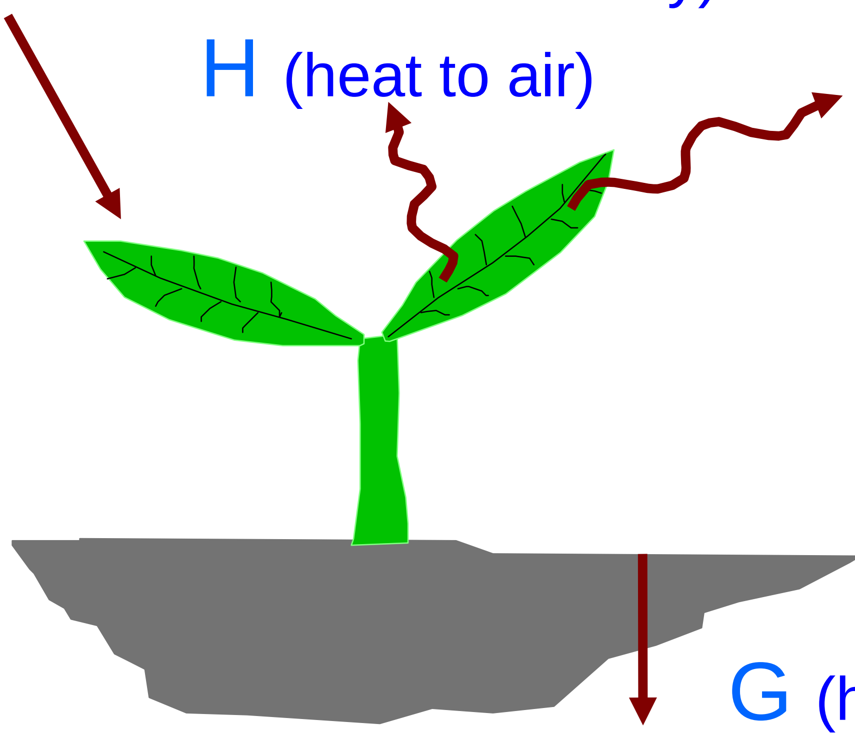


Aerodynamic Transfer caused by Turbulence and Gradients

Illustration of Turbulence and Eddy Diffusivity to Students --- *soap bubbles*

ET is also constrained by Energy Balance

$$ET = R_n - G - H$$



The energy balance includes all major sources (R_n) and consumers (ET, G, H) of energy

Basic Truth: Evaporation consumes Energy

Combination of Energy Balance and Aerodynamics: Penman-Monteith

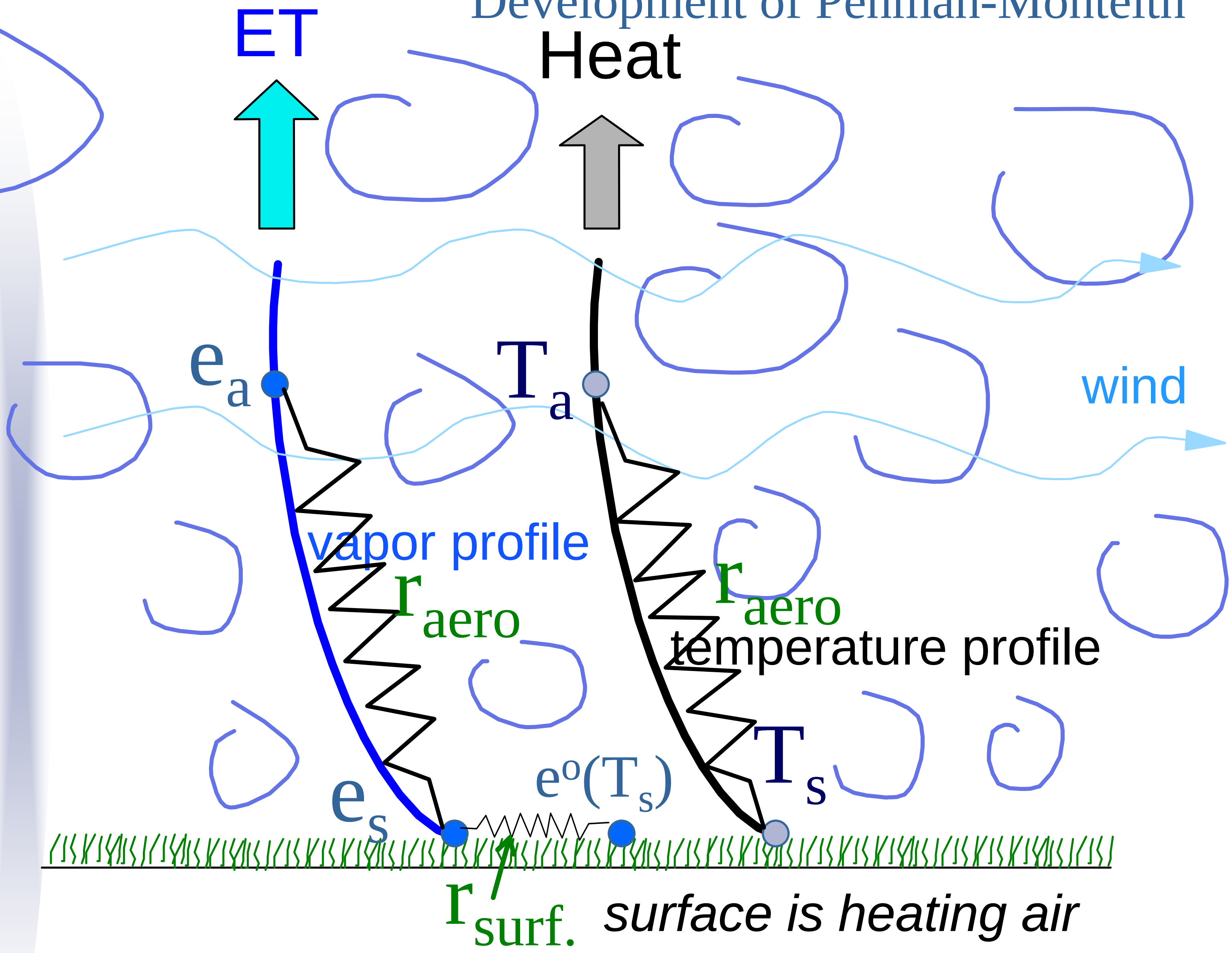
$$ET = \left(\frac{\Delta(R_n - G) + K_{time}\,\rho_a\, c_p \dfrac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \dfrac{r_s}{r_a}\right)} \right) / \lambda$$

f (Solar Radiation) f (Temperature) f(Wind Speed) f (Humidity)

r_a = aerodynamic resistance

r_s = bulk surface resistance (canopy / stomatal)

Development of Penman-Monteith



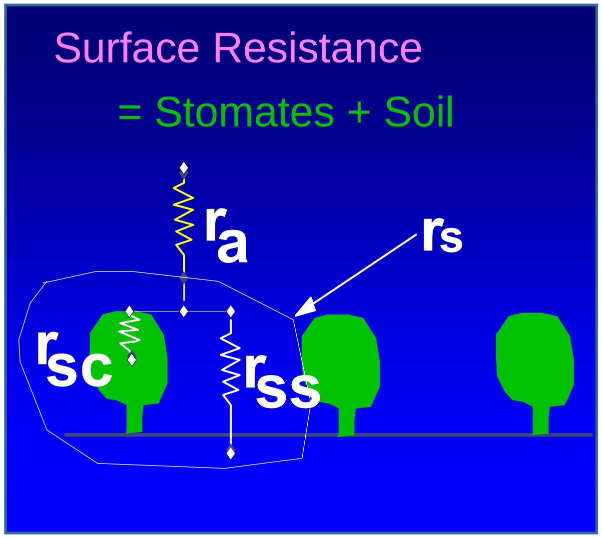
Aerodynamic Turbulence + Vapor and T Gradients → ET, H

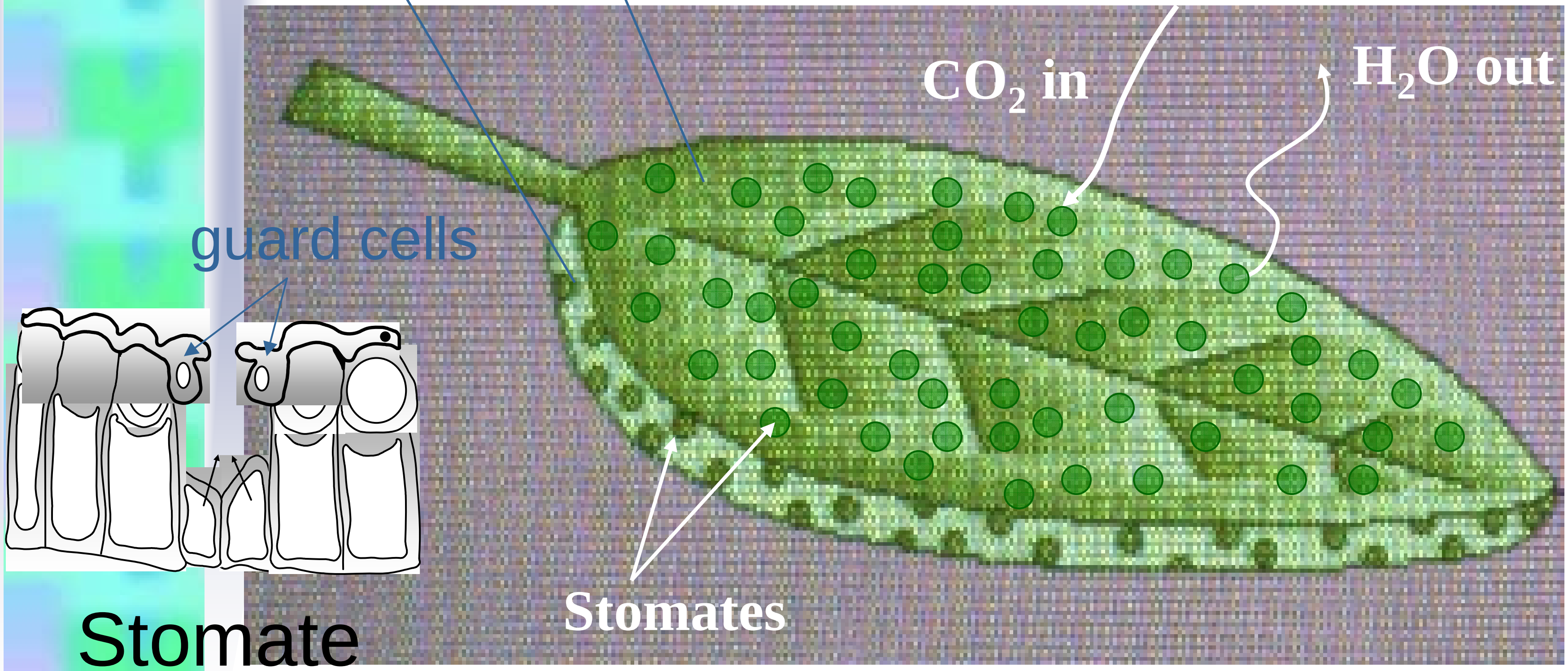
Bulk Stomatal Resistance

Water Vapor flow out of stomates
CO_2 flows in for Photosynthesis

inside of leaf is saturated ($e^o(T_s)$)

outside of leaf is unsaturated (e_s)





Reference ET:
A Living Evaporation Index

30 s m^{-1}* *(daytime hourly)

***45 s m^{-1}* *(24-hr)* for alfalfa**

ASCE Penman-Monteith

$$ET = \left(\frac{\Delta(R_n - G) + K_{time}\,\rho_a\, c_p \dfrac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \dfrac{r_s}{r_a}\right)} \right) / \lambda$$

C_n and C_d are constants

Standardized ASCE Penman-Monteith

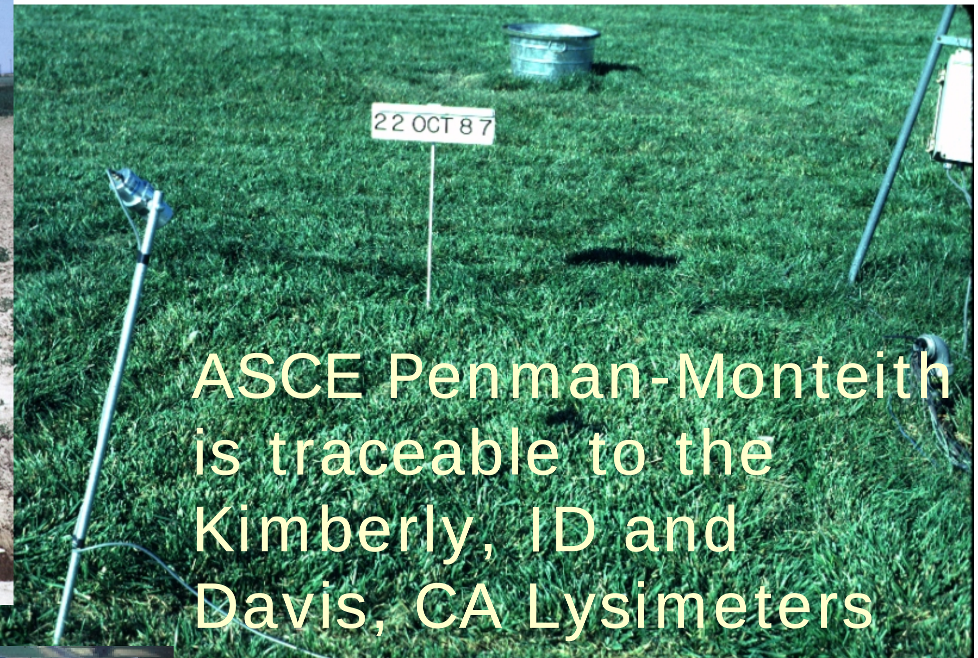
$$ET_{ref} = \frac{0.408\,\Delta(R_n - G) + \gamma \dfrac{C_n}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)}$$

f (Solar Radiation)

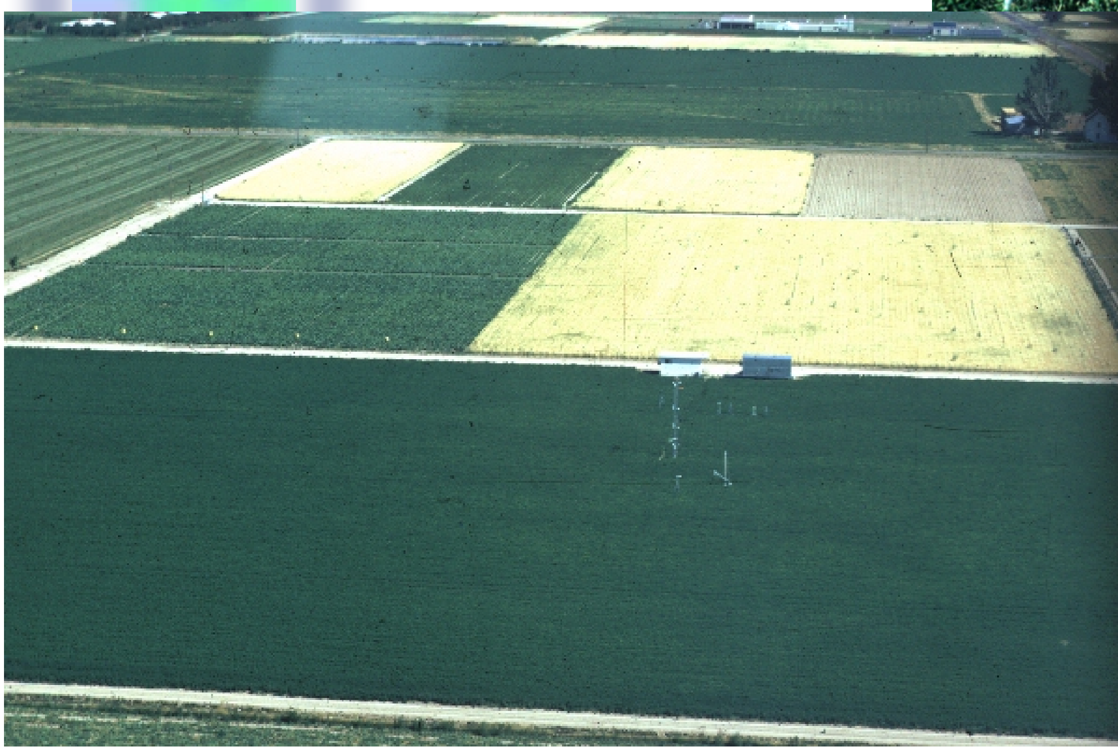
f (Temperature)

Wind Speed

f (Humidity)



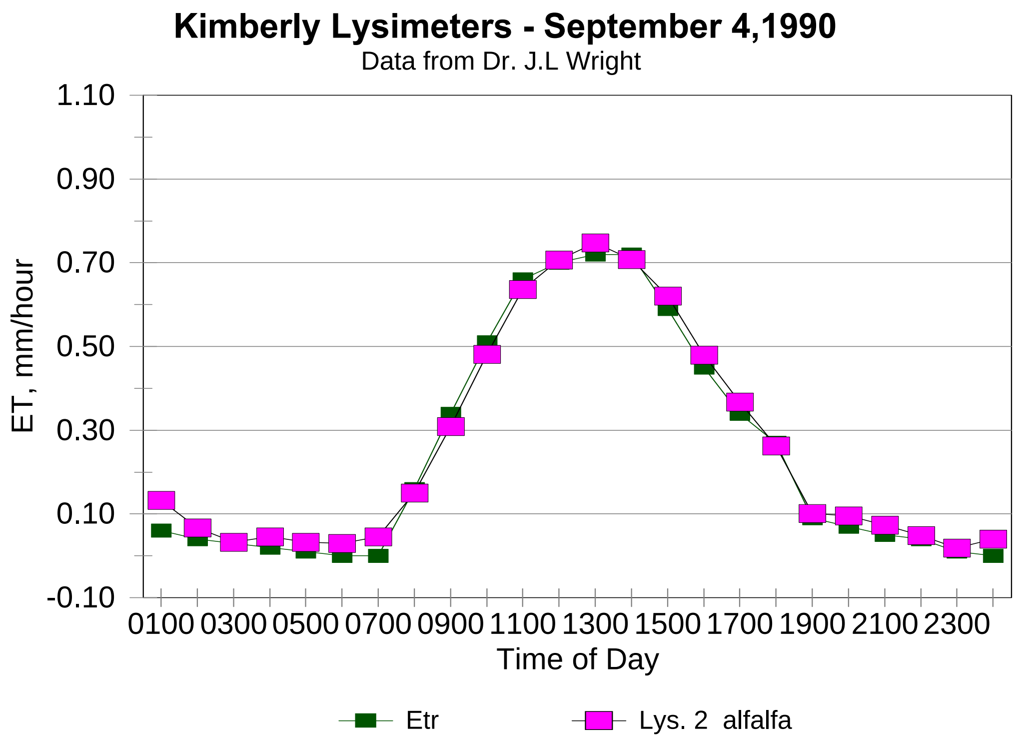
ASCE Penman-Monteith
is traceable to the
Kimberly, ID and
Davis, CA Lysimeters

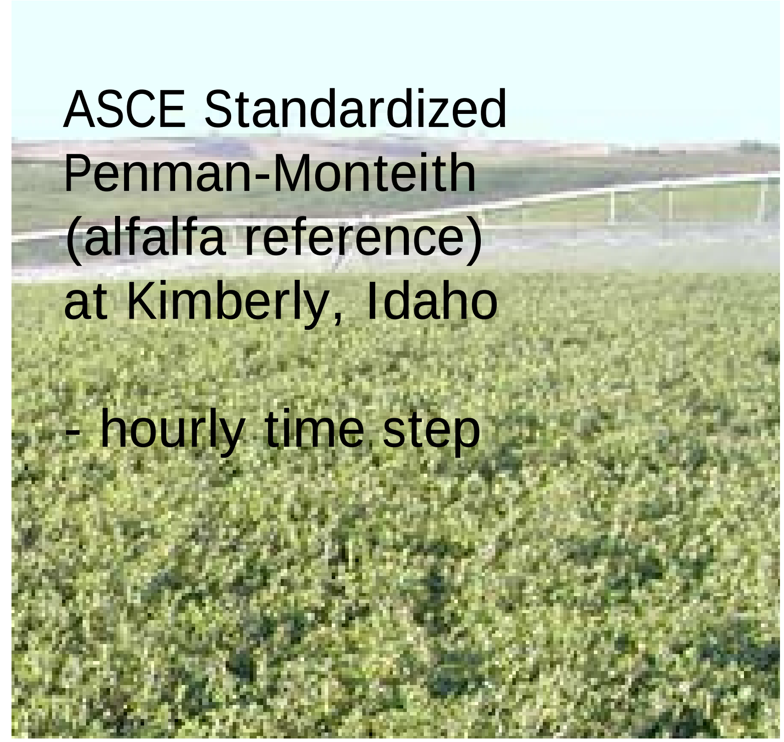


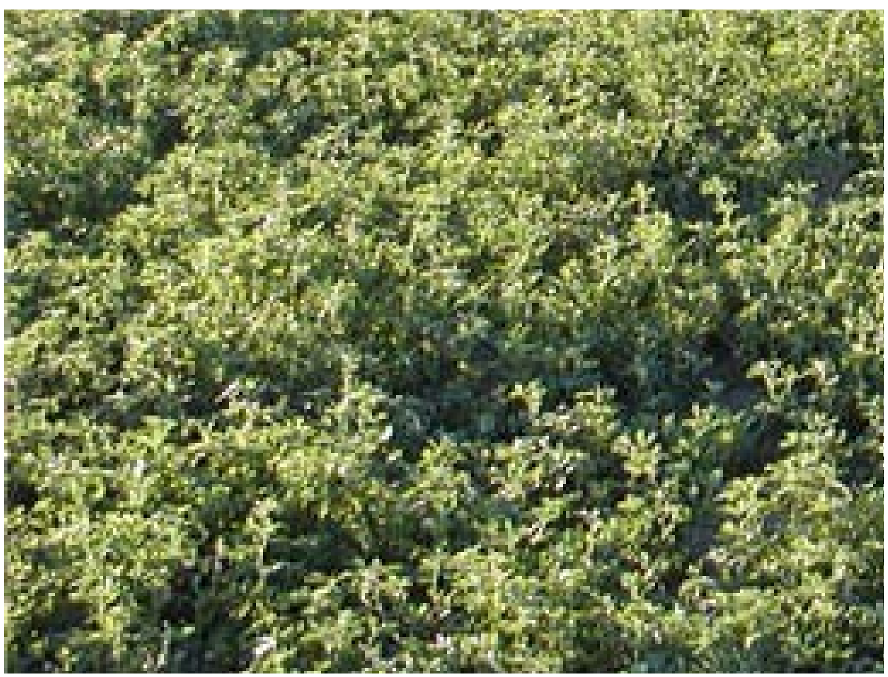
Comparisons with Measurements

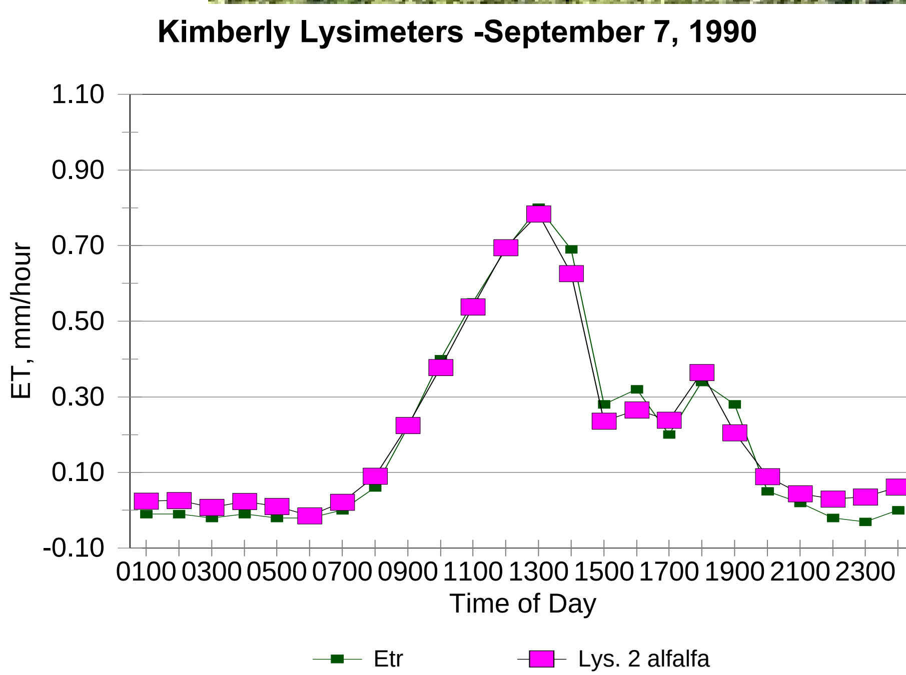
Weighing Lysimeter System at Kimberly, Idaho

Dr. James L. Wright, USDA-ARS

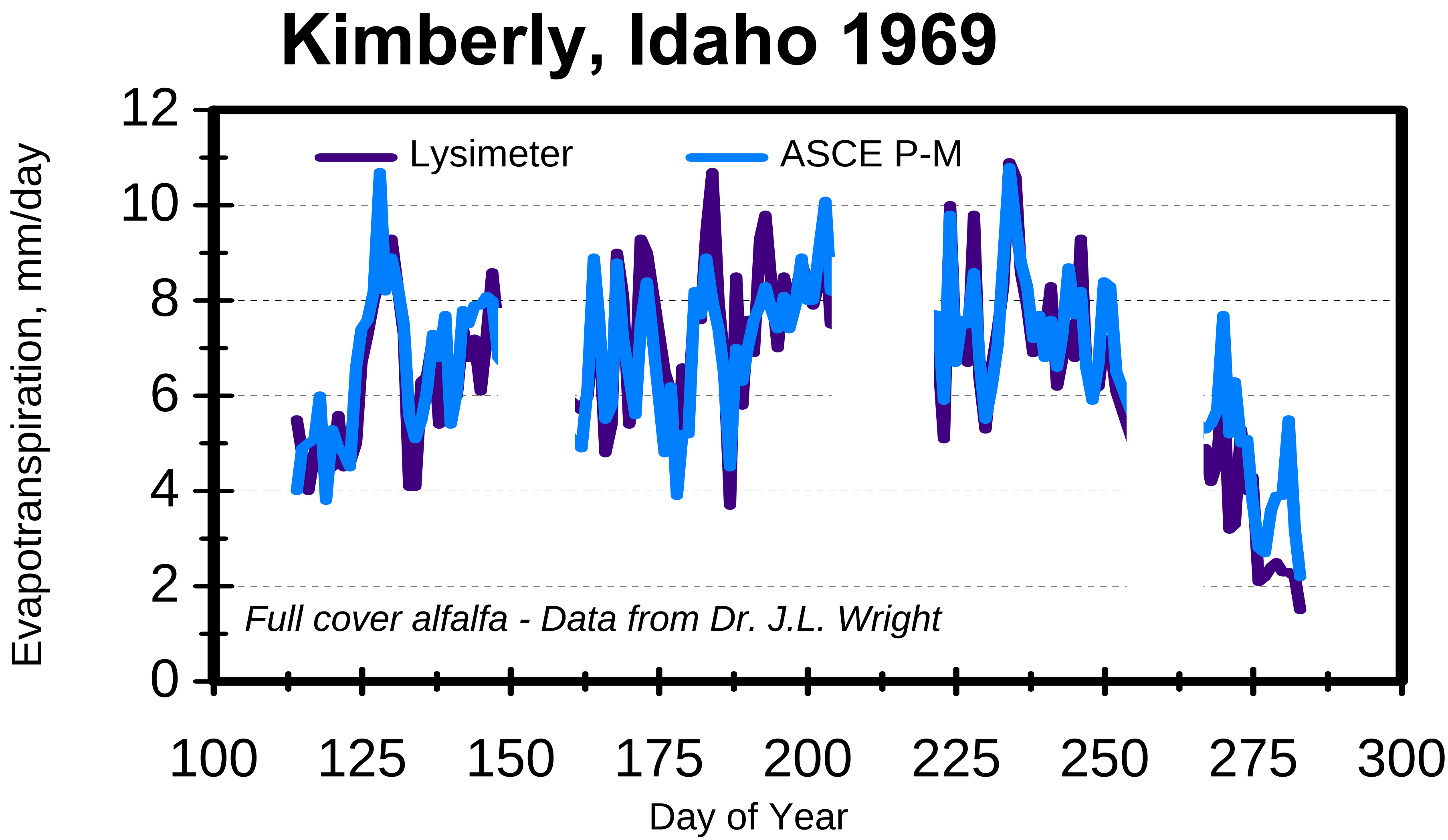

Kimberly Lysimeters - September 4,1990
Data from Dr. J.L Wright
ET, mm/hour
1.10
0.90
0.70
0.50
0.30
0.10
-0.10
0100 0300 0500 0700 0900 1100 1300 1500 1700 1900 2100 2300
Time of Day
Etr
Lys. 2 alfalfa


ASCE Standardized
Penman-Monteith
(alfalfa reference)
at Kimberly, Idaho
- hourly time step



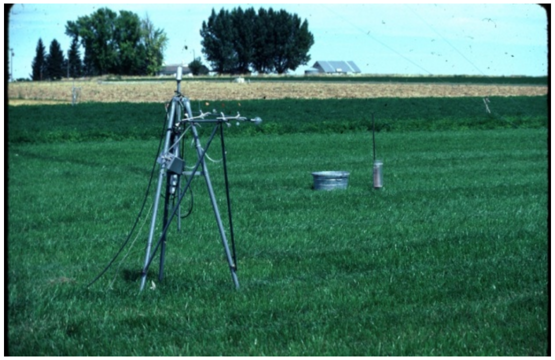

Kimberly Lysimeters -September 7, 1990
ET, mm/hour
1.10
0.90
0.70
0.50
0.30
0.10
-0.10
0100 0300 0500 0700 0900 1100 1300 1500 1700 1900 2100 2300
Time of Day
Etr
Lys. 2 alfalfa

Good day to day correspondance with lysimeter



Choice of Reference Type:

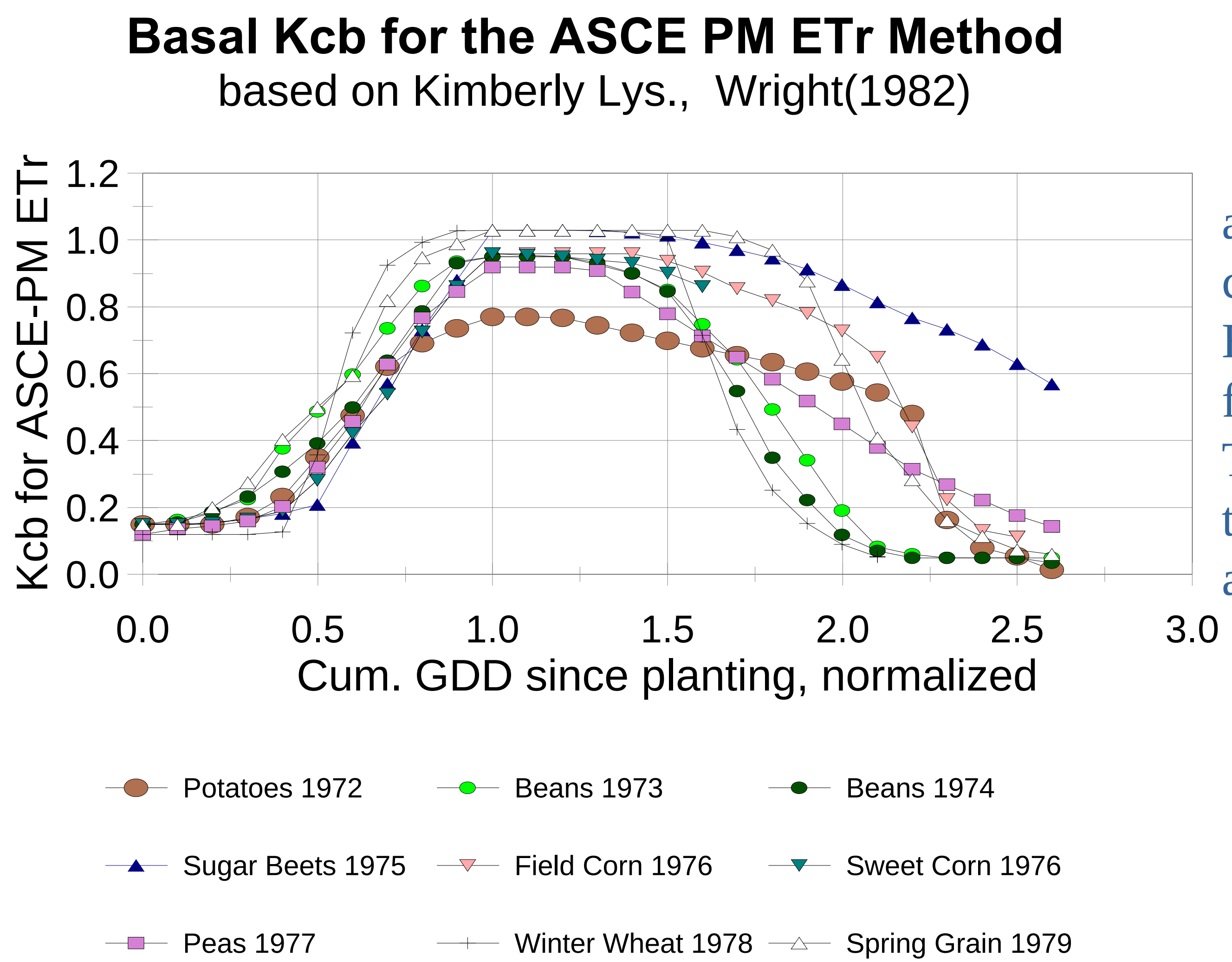
- <u>Grass reference</u> ET_o has a long history of application in urban areas and for agriculture in much of the U.S.



- <u>Alfalfa reference</u> ET_r has a long history for agricultural application in the midwest and northwest

- Theoretical arguments for both short and tall reference crops have been made by Perrier (1980) and Pereira et al. (1999)

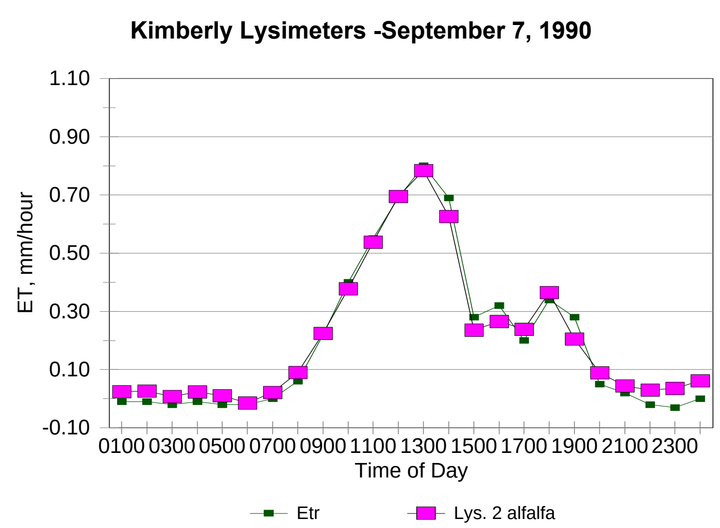
An argument for ET_r is that Maximum K_{cb} tends toward 1.0



and aerodynamic characteristics of ET_r are similar to field crops. Therefore, better transferability across climates.

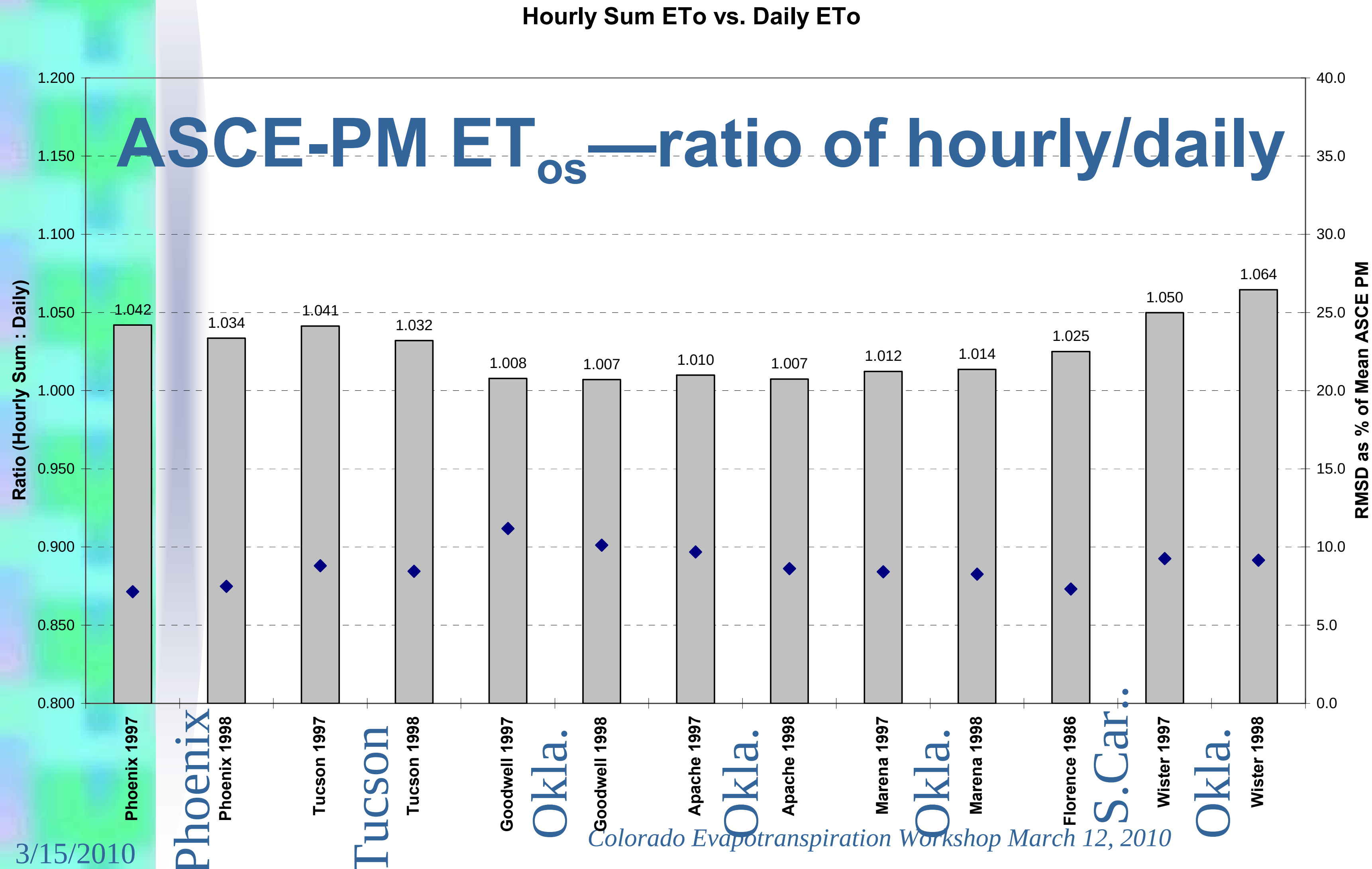
Time Step Considerations – daily vs. hourly

- **For the same data quality, hourly is "a few percent" better than daily**
  - interactions among within-day trends in wind speed, humidity, temperature, radiation are captured in the ET_{ref} calculation



Time Step Considerations

–Generally, differences between summed hourly and daily are within 5%, especially over five or more days.

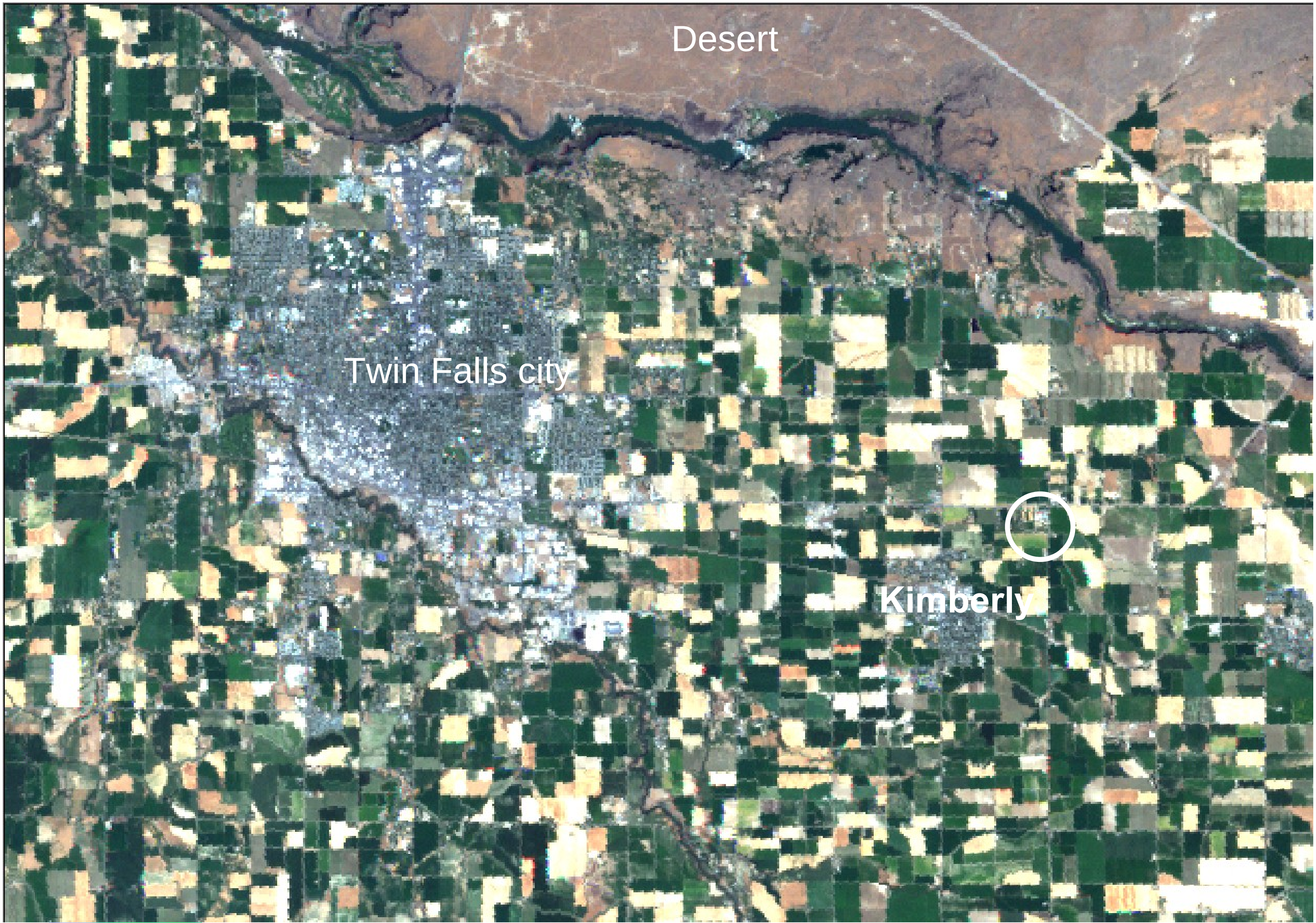


Quality Assessment/Quality Control

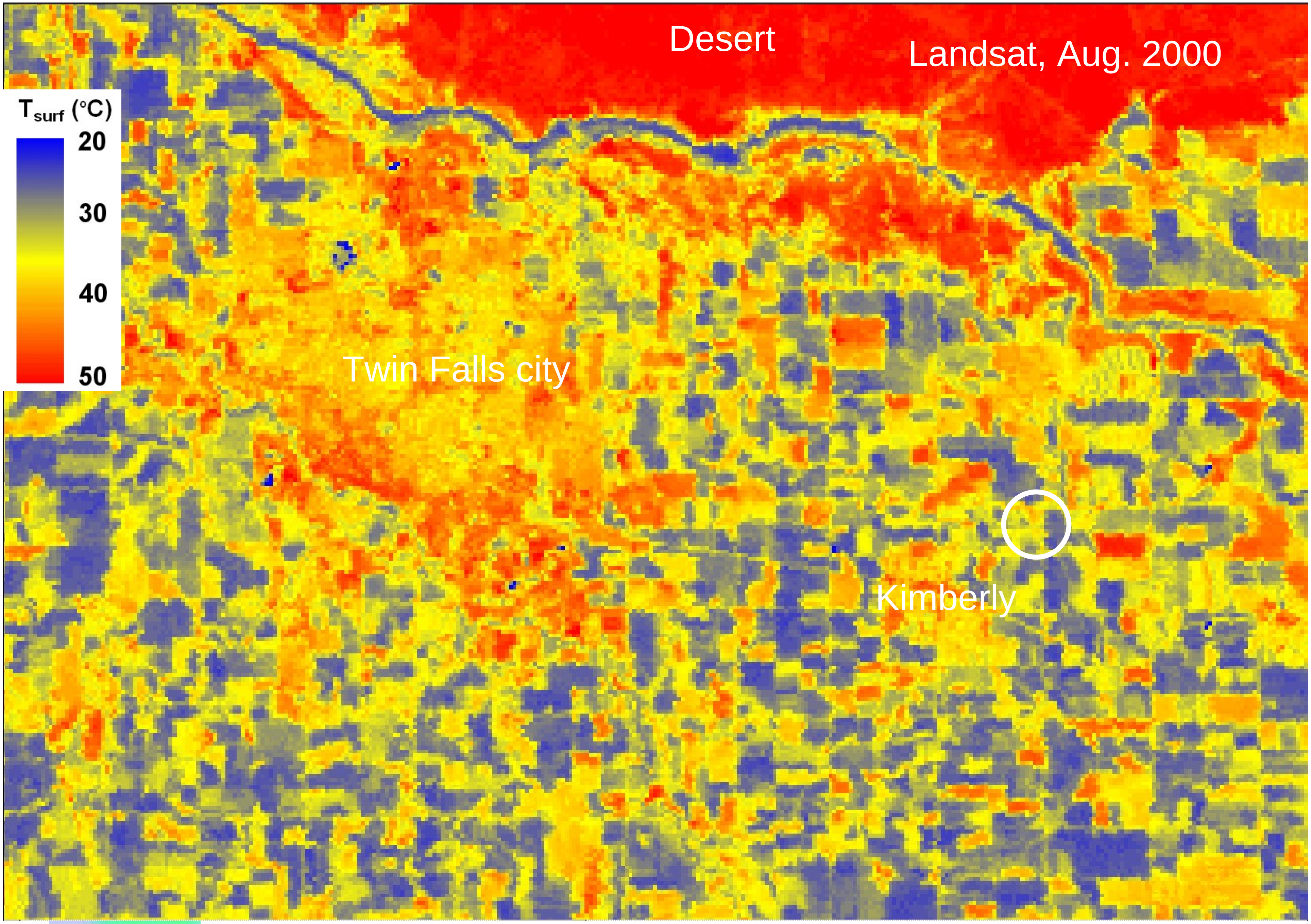
----- I'm for it

Weather Station Siting (The PM ET_r equation 'expects' 'Reference Conditions')

- **Minimize Impacts of Station and Area Dryness on**
  - **Air Temperature**
  - **Humidity**
  - **Wind Speed**



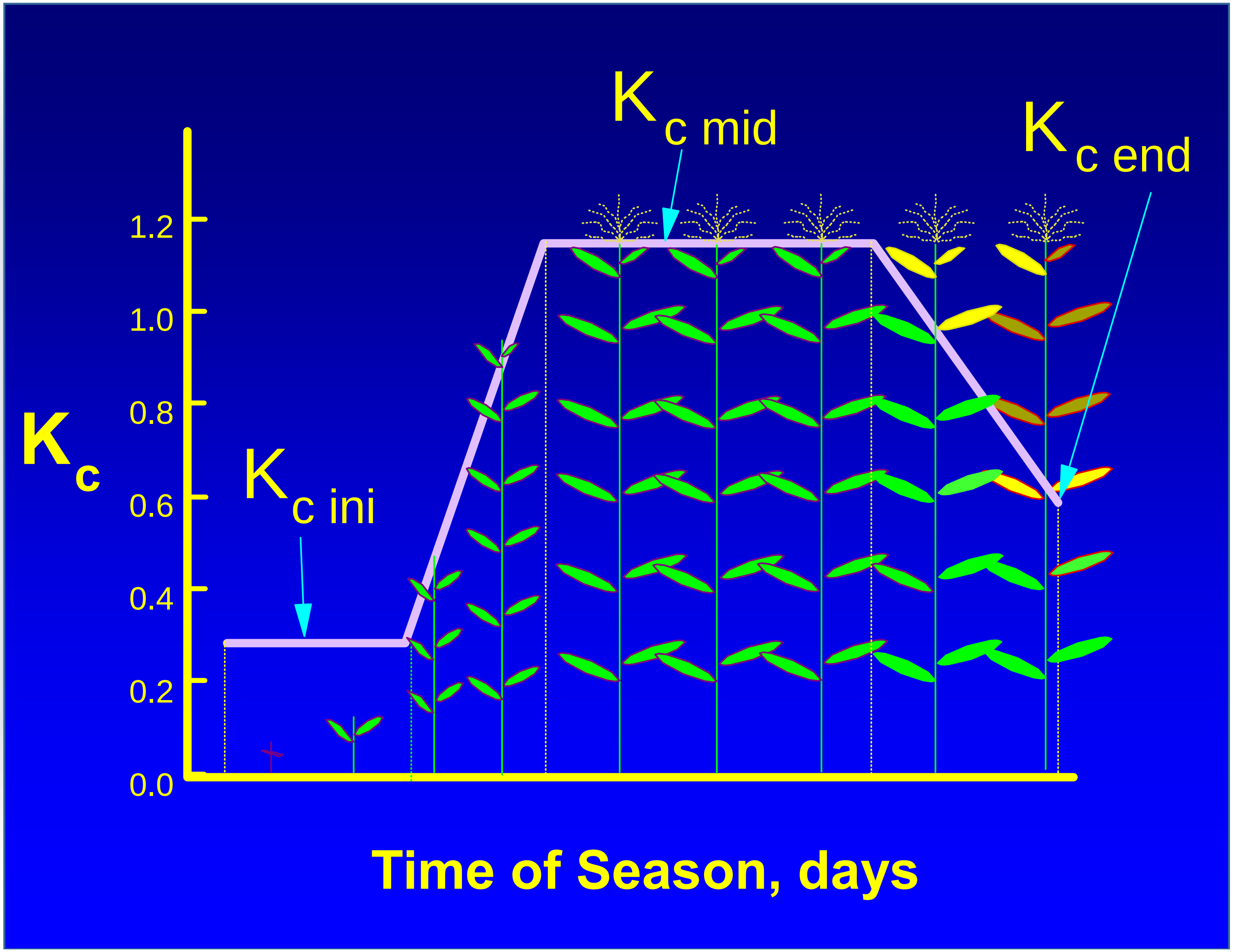
Landsat image for Twin Falls, Idaho, USA



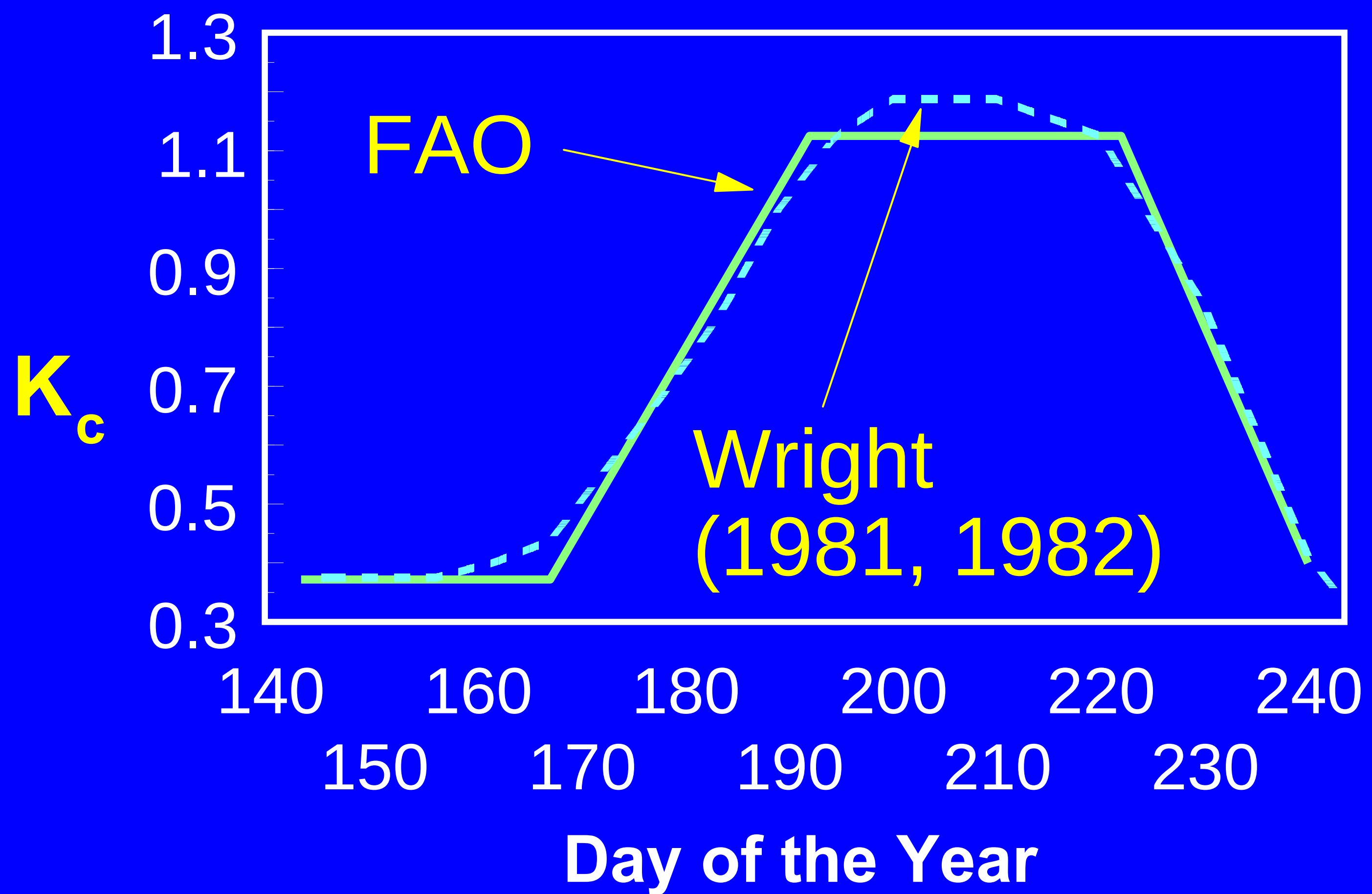
Surface Temperature from Landsat

Crop Coefficients

Crop Coefficient = ET/ET_{ref}



Crop Coefficient Curve Types



“Mean” vs. Dual K_c Approaches

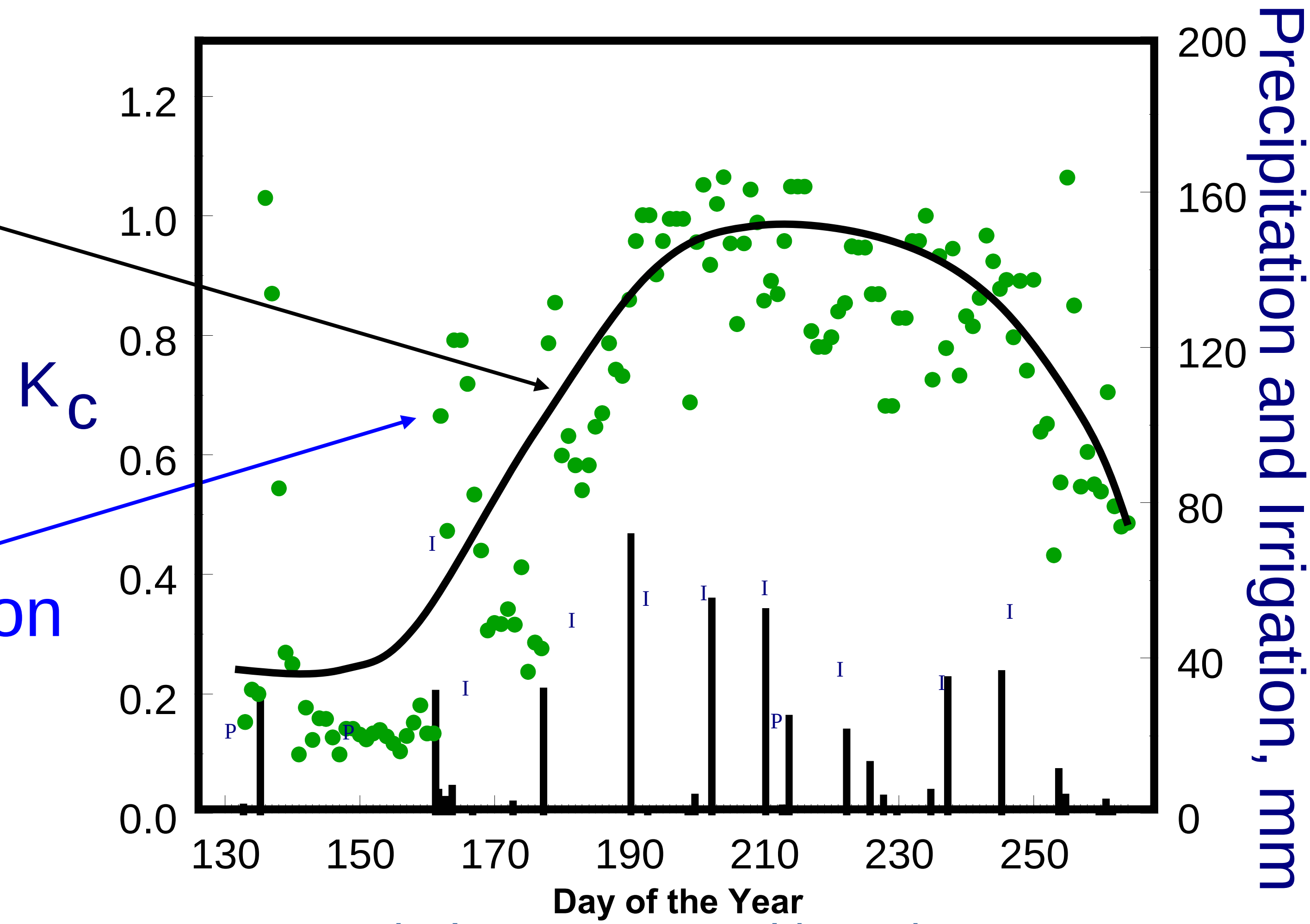
K_c from Lysimeter

each dot is one day

Sweet Corn-- Kimberly, Idaho, 1976

"Mean" Curve averaging "Spikes"

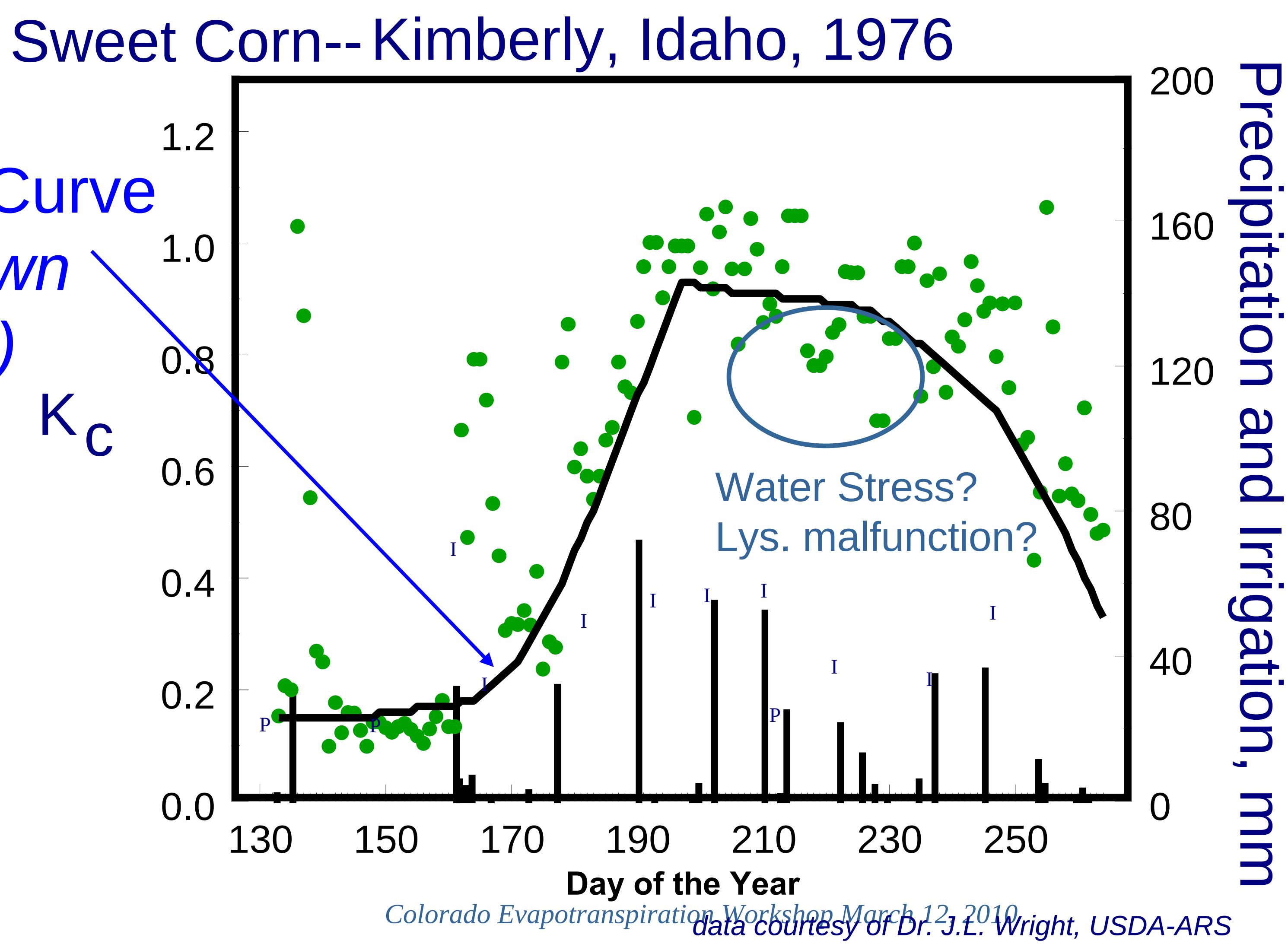
Wet Soil Evaporation "Spikes" (K_e)



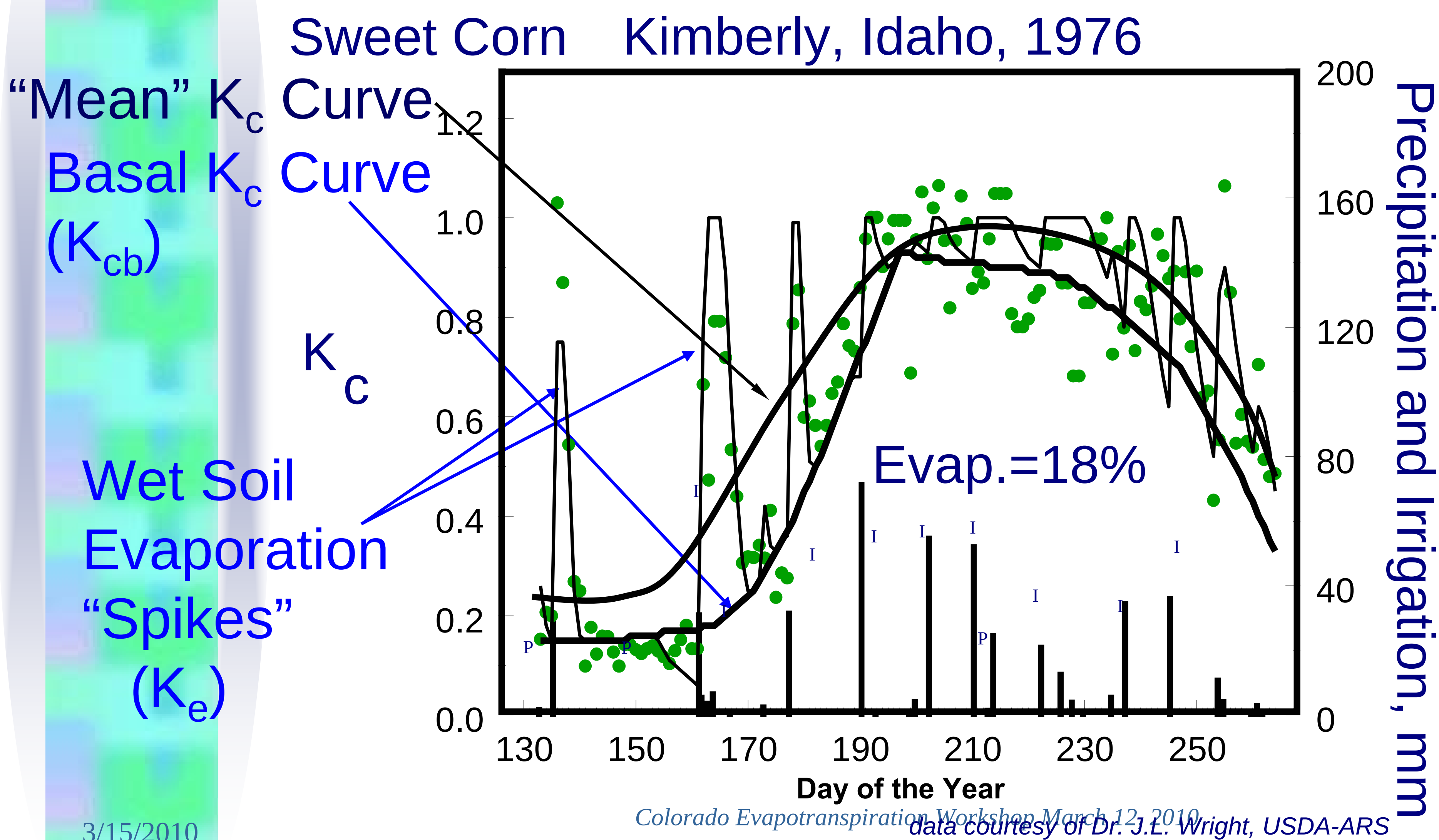
data courtesy of Dr. J.L. Wright, USDA-ARS

K_c from Lysimeter

Basal K_c Curve (K_{cb}) *(drawn by Wright)*



The "Dual K_c" method Splits Soil Evaporation from Transpiration



'Dual' K_c Procedure

$$\frac{ET}{ET_{ref}} =$$

$$K_c = K_s K_{cb} + K_e$$

K_s = water stress (0 - 1)

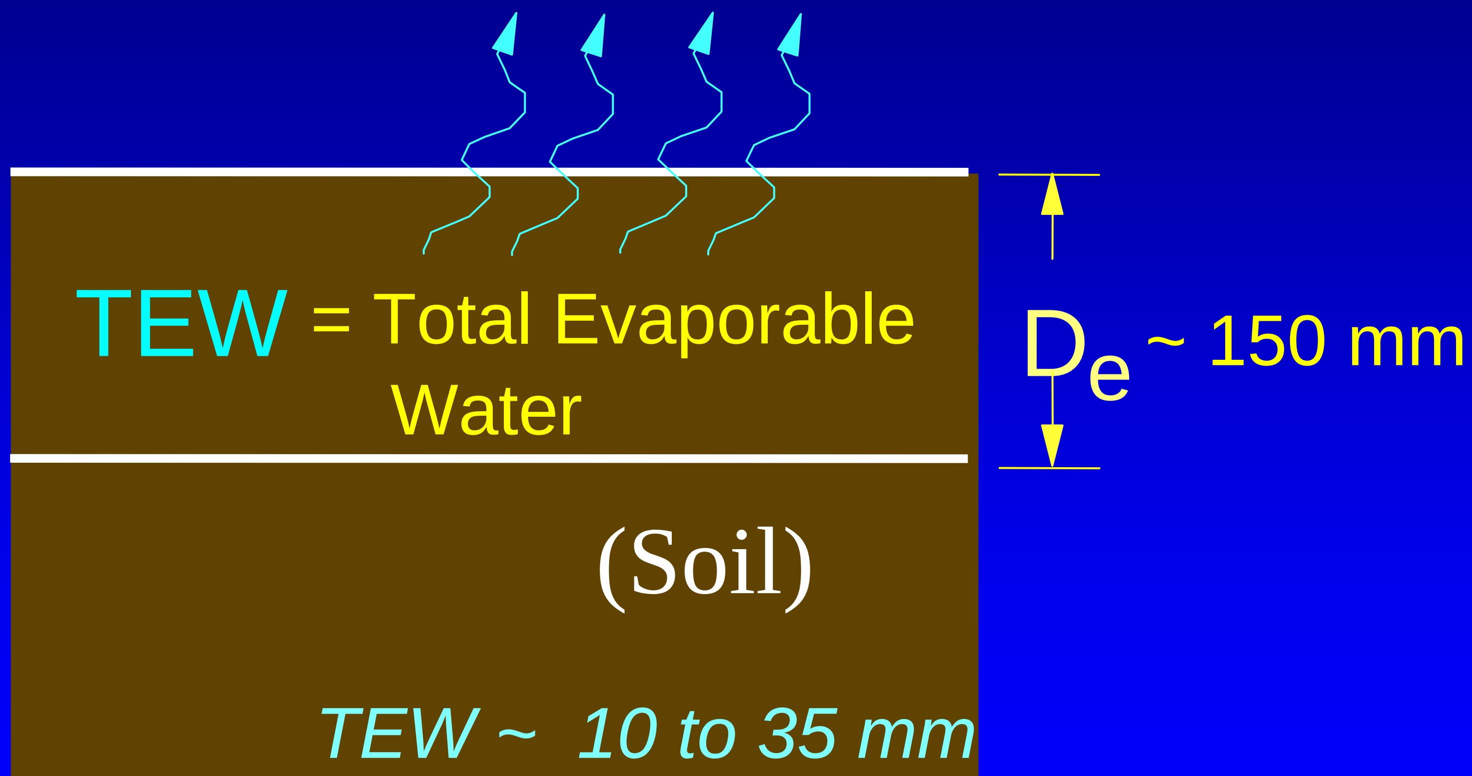
K_{cb} = basal K_c *(dry surface)*

K_e = evaporation coefficient

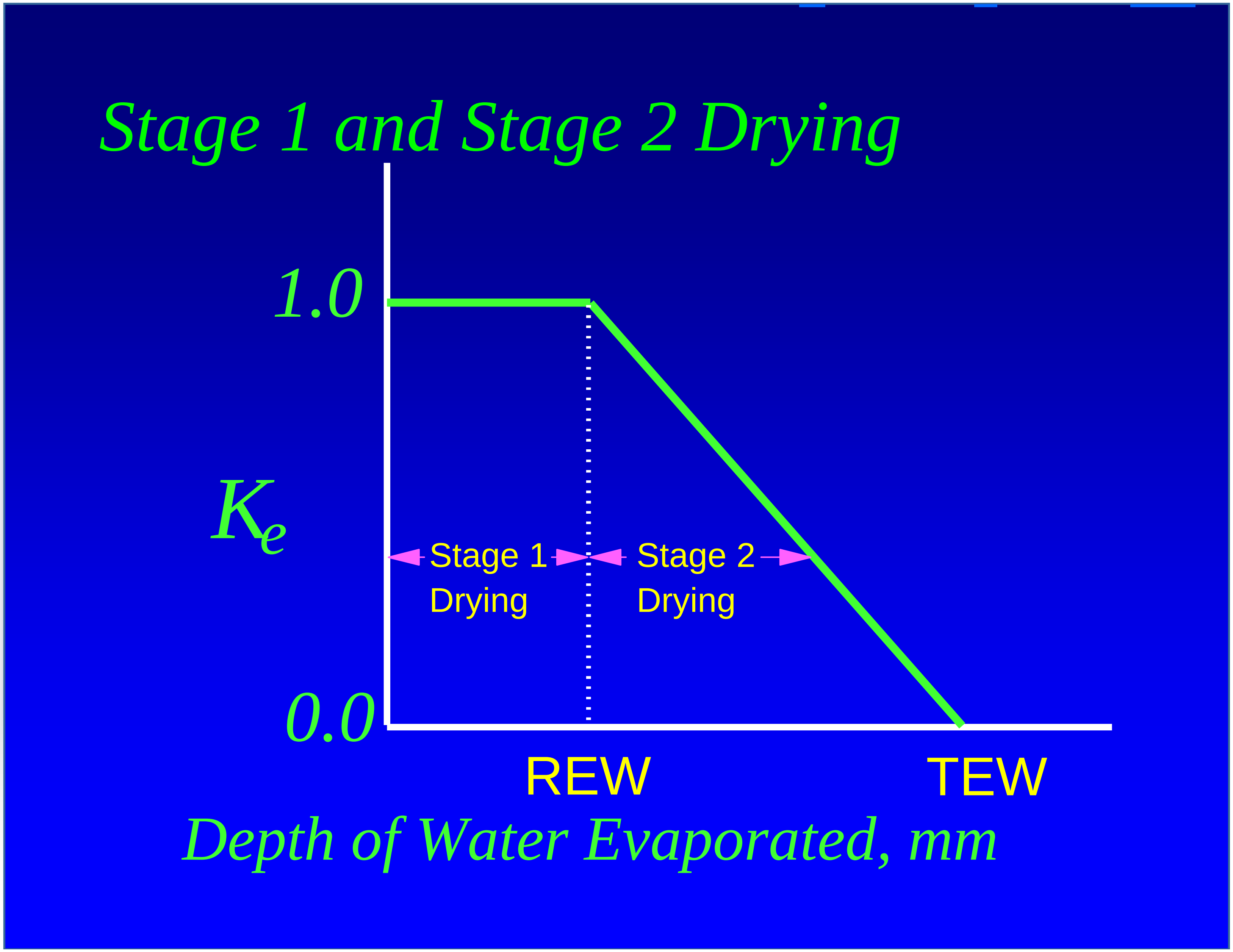
Evaporation Coefficient - K_e

FAO-56 Simple Drying Function

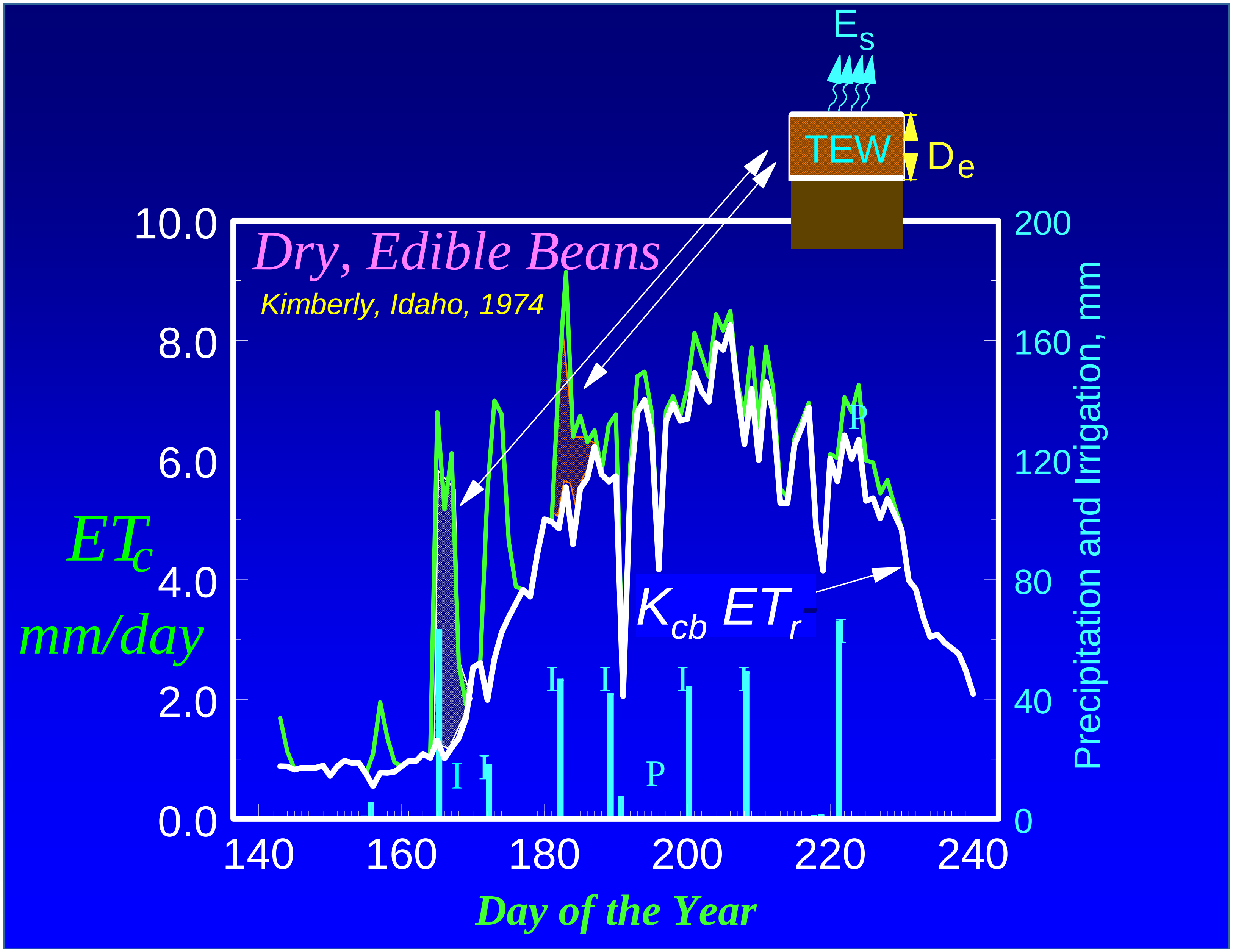
$$E_s = K_e \, ET_{ref}$$



Evaporation Coefficient – $K_e = E_s/ET_{ref}$

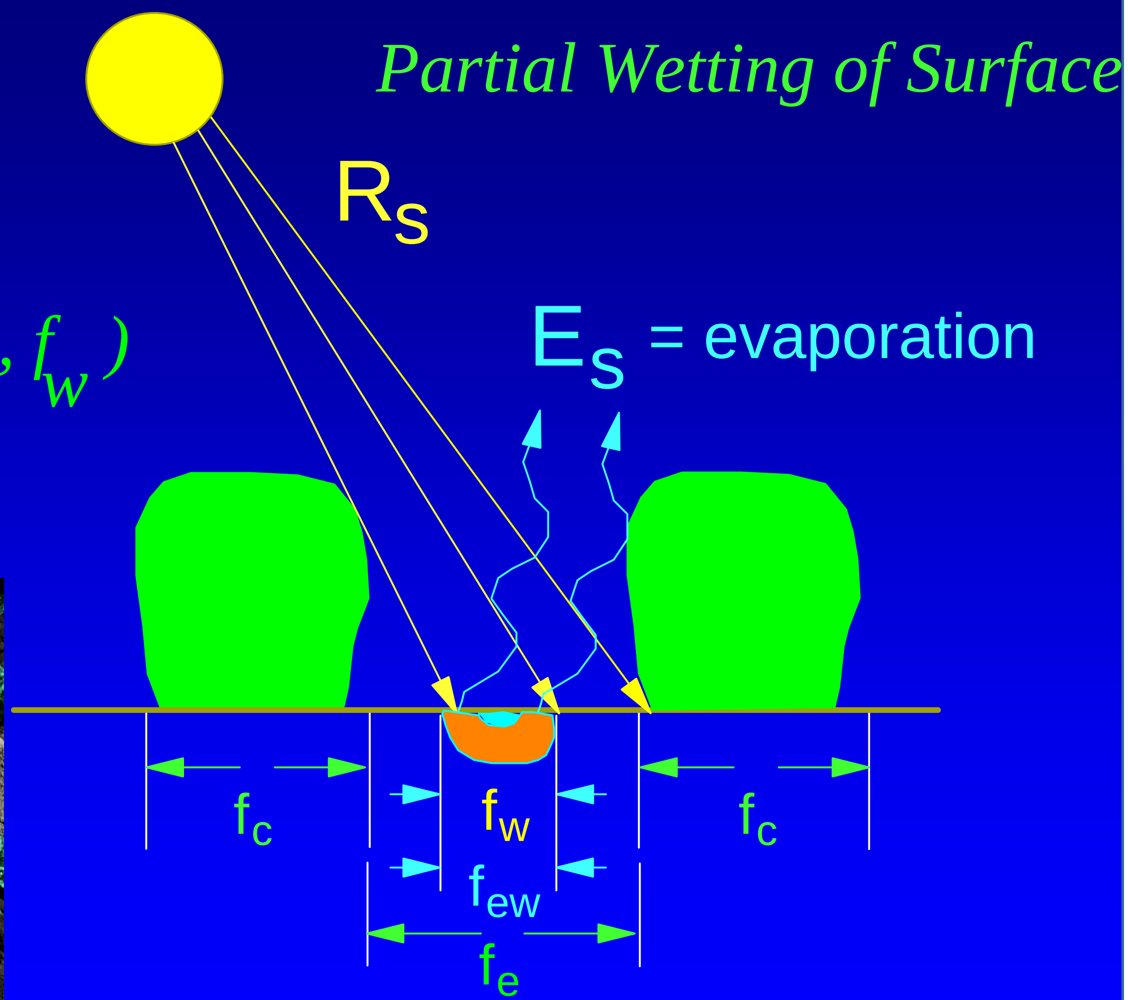


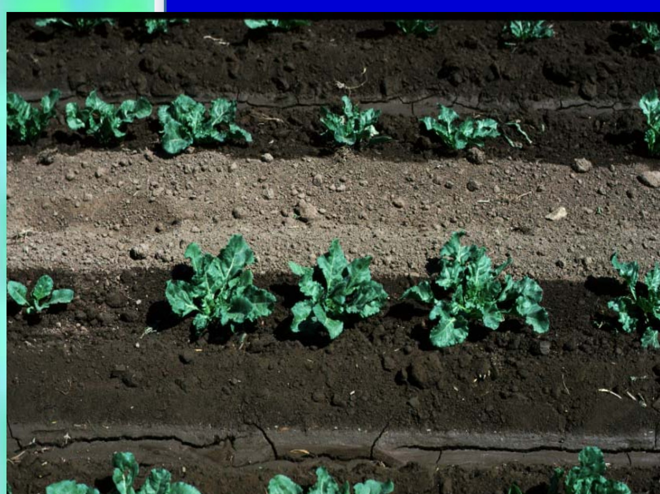
'Dual' Crop Coefficient



Partial Surface Wetting/Drying

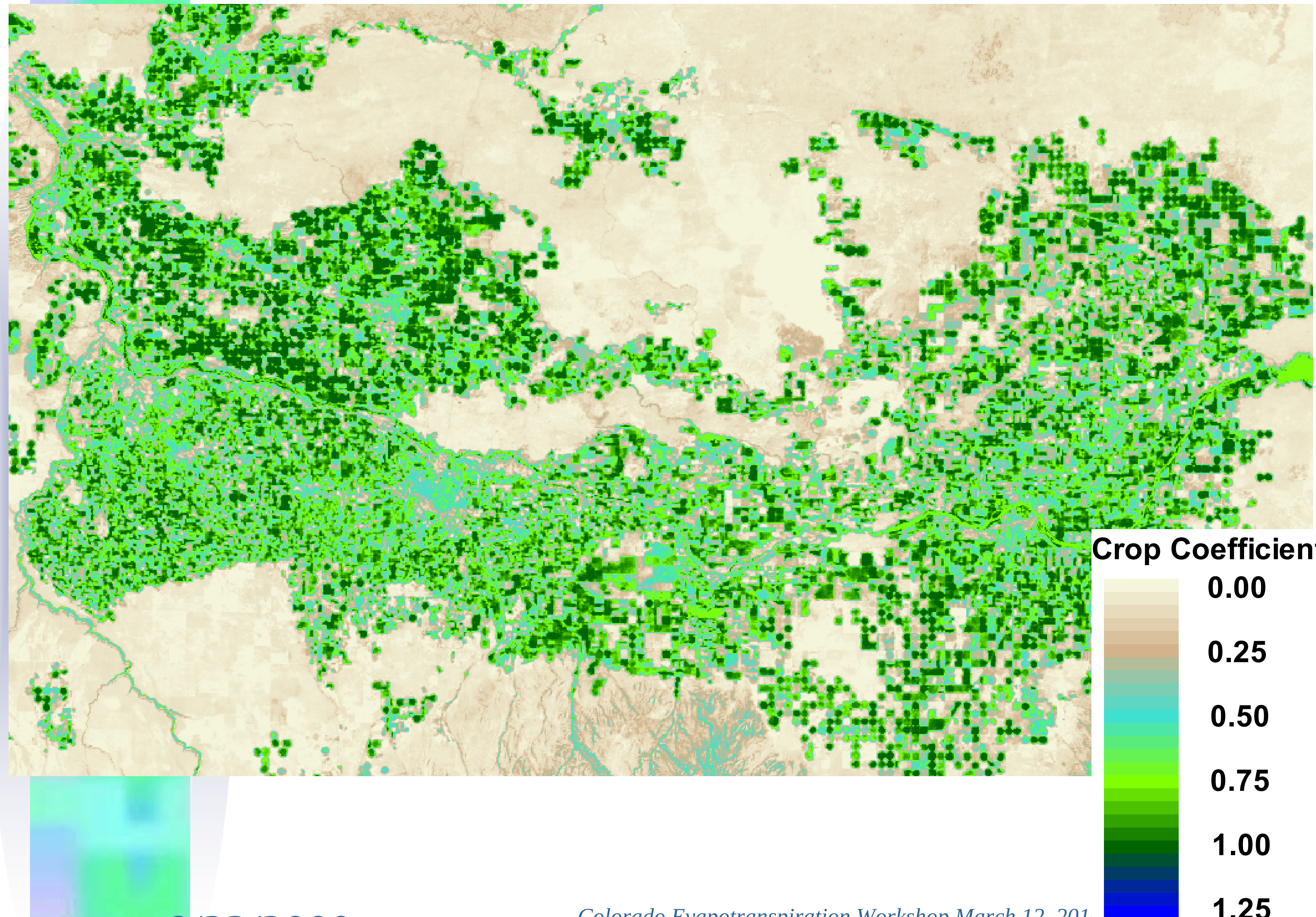
$$f_{ew} = min(1 - f_c, f_w)$$





Challenges with K_c Curves

The “Population” of K_c varies among fields

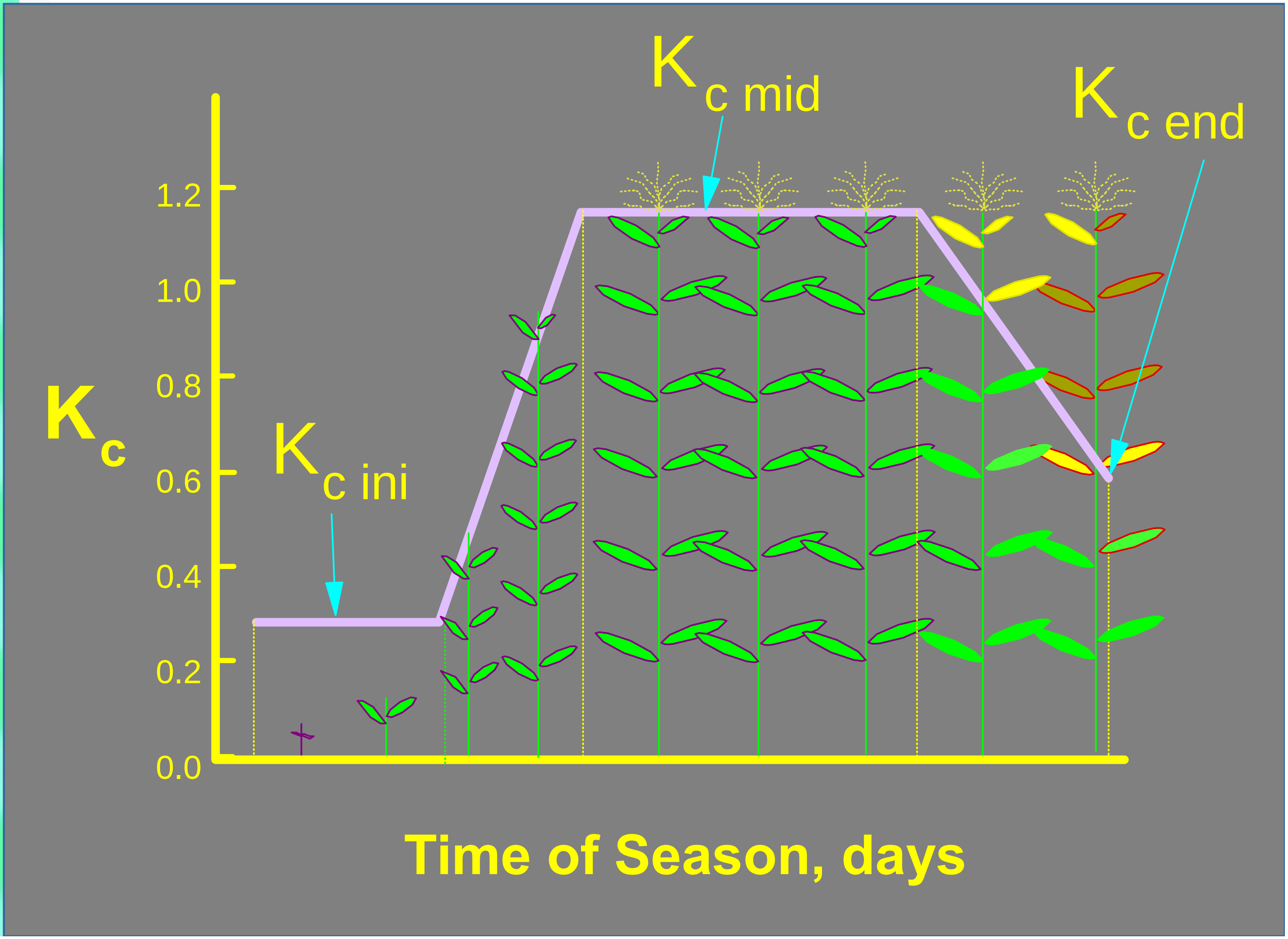


8/22/2000

Different Time Bases

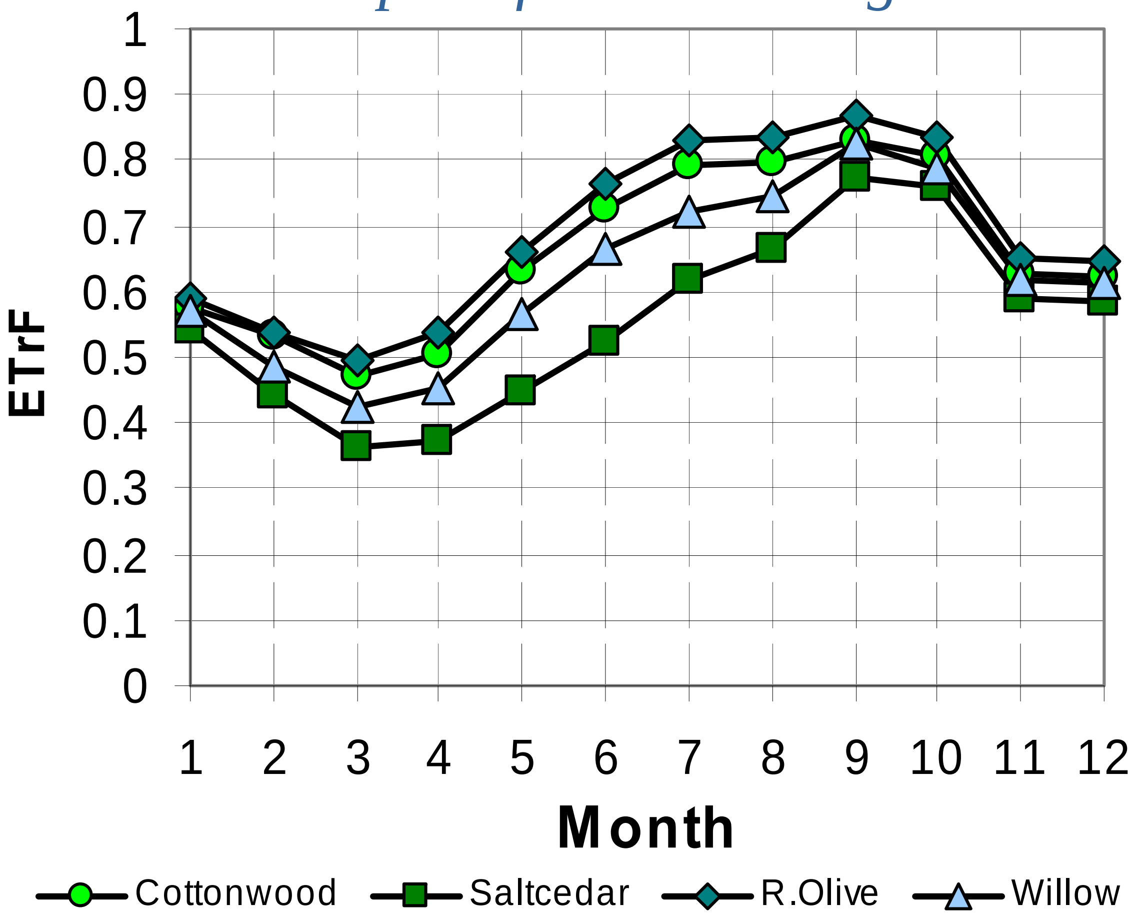
Four types

1. Time in days from Greenup (or Planting) to Termination (SCS, FAO)

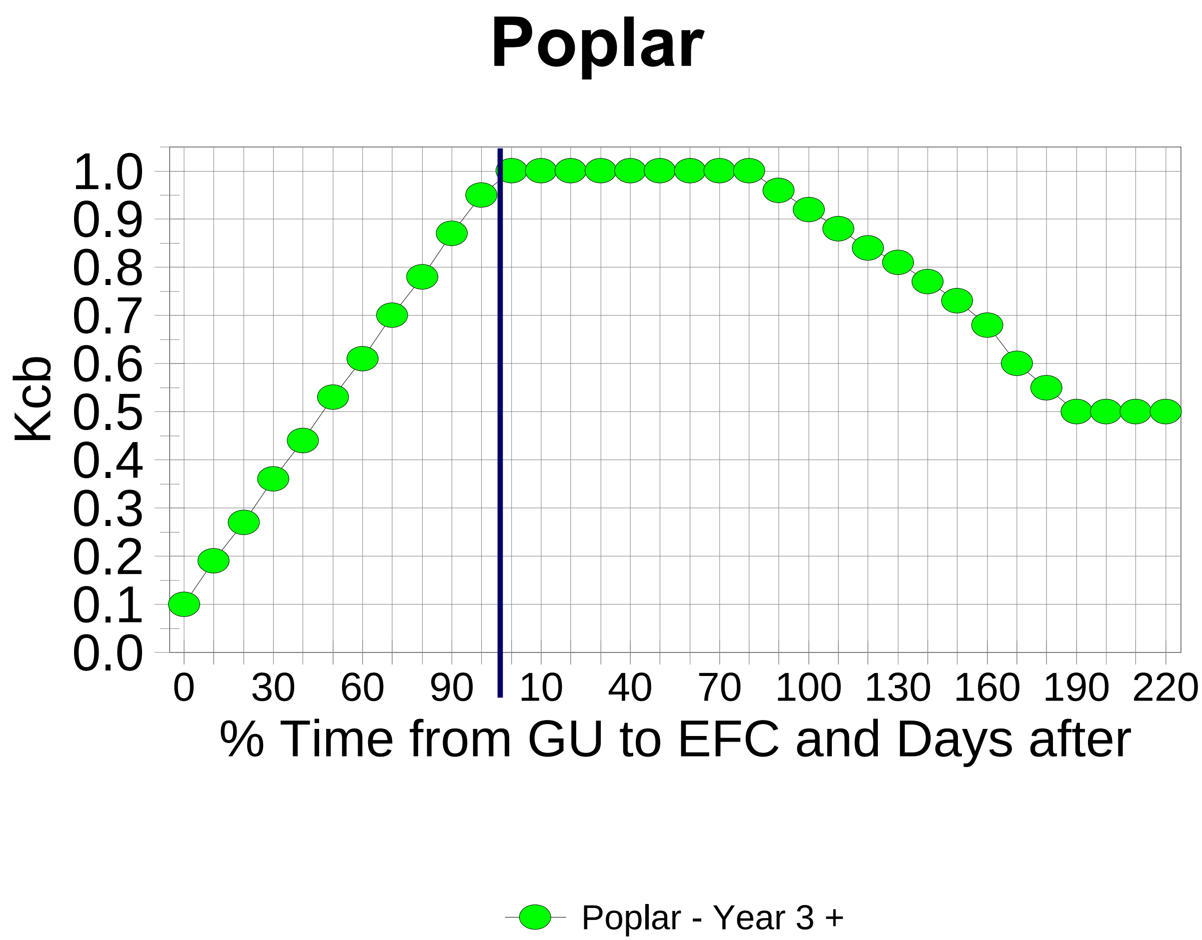


1. <u>Time in days</u> from Greenup (or Planting) to Termination (SCS, FAO)

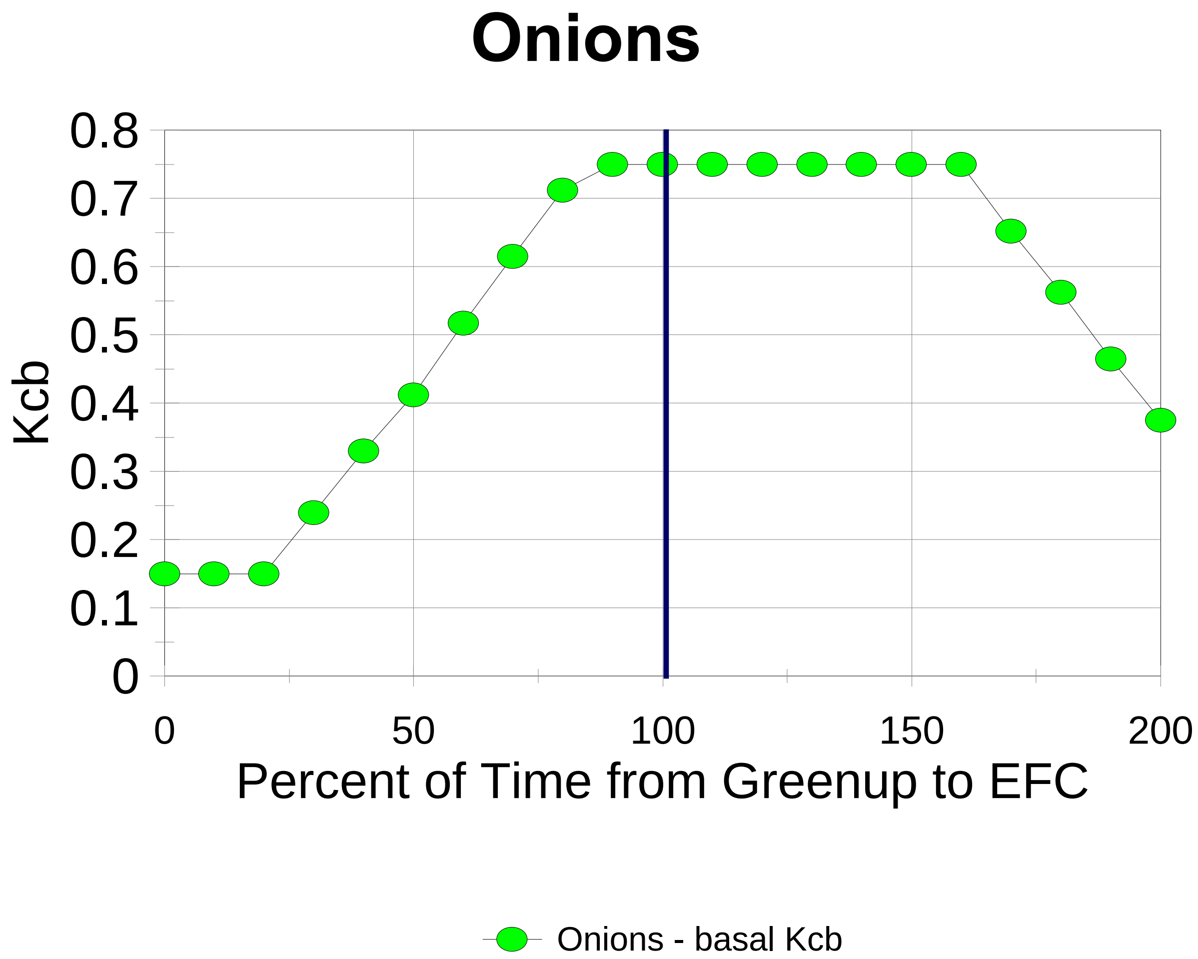
sometimes simplest for natural vegetation



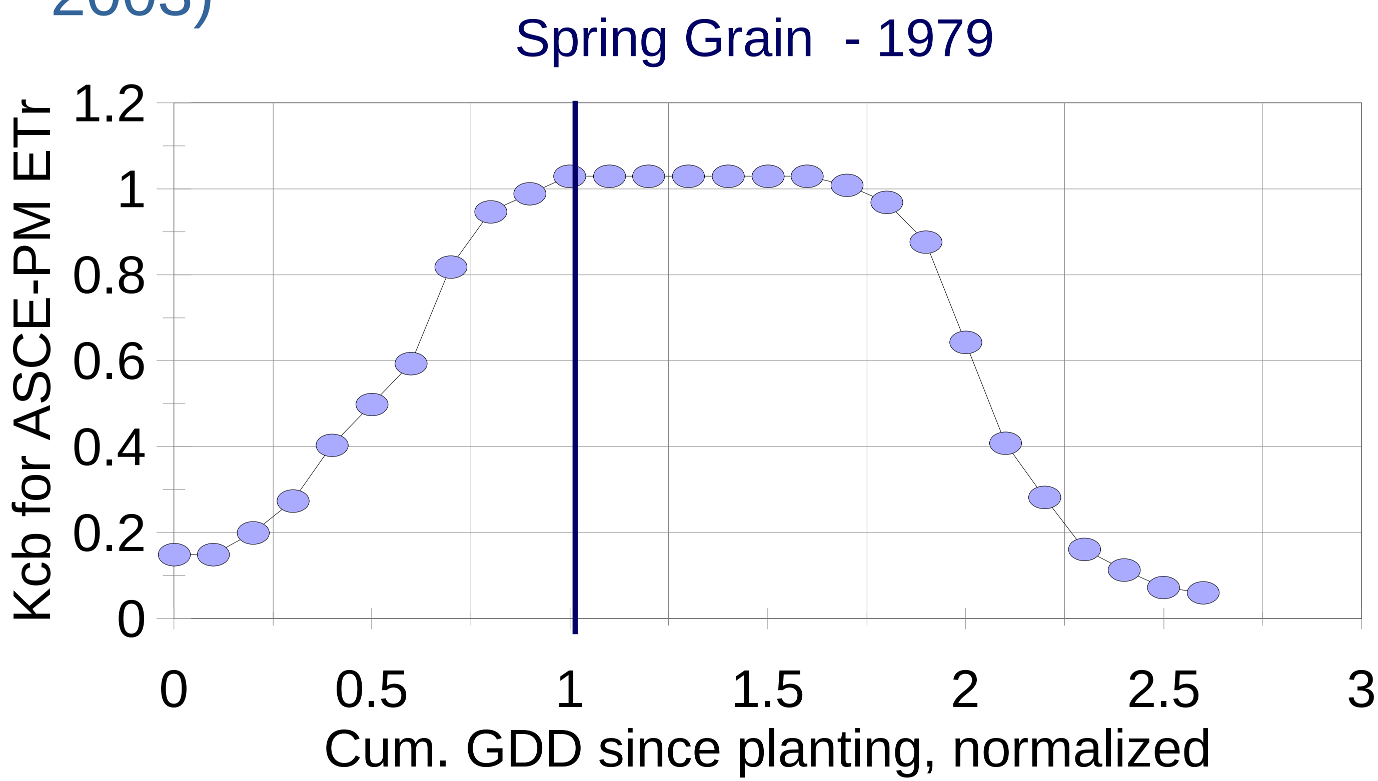
2. Percent Time from Greenup (or Planting) to Effective Full Cover (EFC) and Days after EFC (Wright, 1981, 1982)



3. Percent Time from Greenup (or Planting) to Effective Full Cover (EFC)
-- over full period



4. Normalized (ratio of) Cumulative Growing Degree Days (GDD) from Planting to Effective Full Cover (Wright, 1998; Allen and Wright, 2003)



$$GDD = max\left(\frac{T_{max} + T_{min}}{2} - T_{base}, 0\right)$$

T_{base} is 0^{o}C for many crops, 5^{o}C for others

Cumulative GDD for Wright (1982) K_{cb}'s as used in Idaho – Allen and Robison (2007)

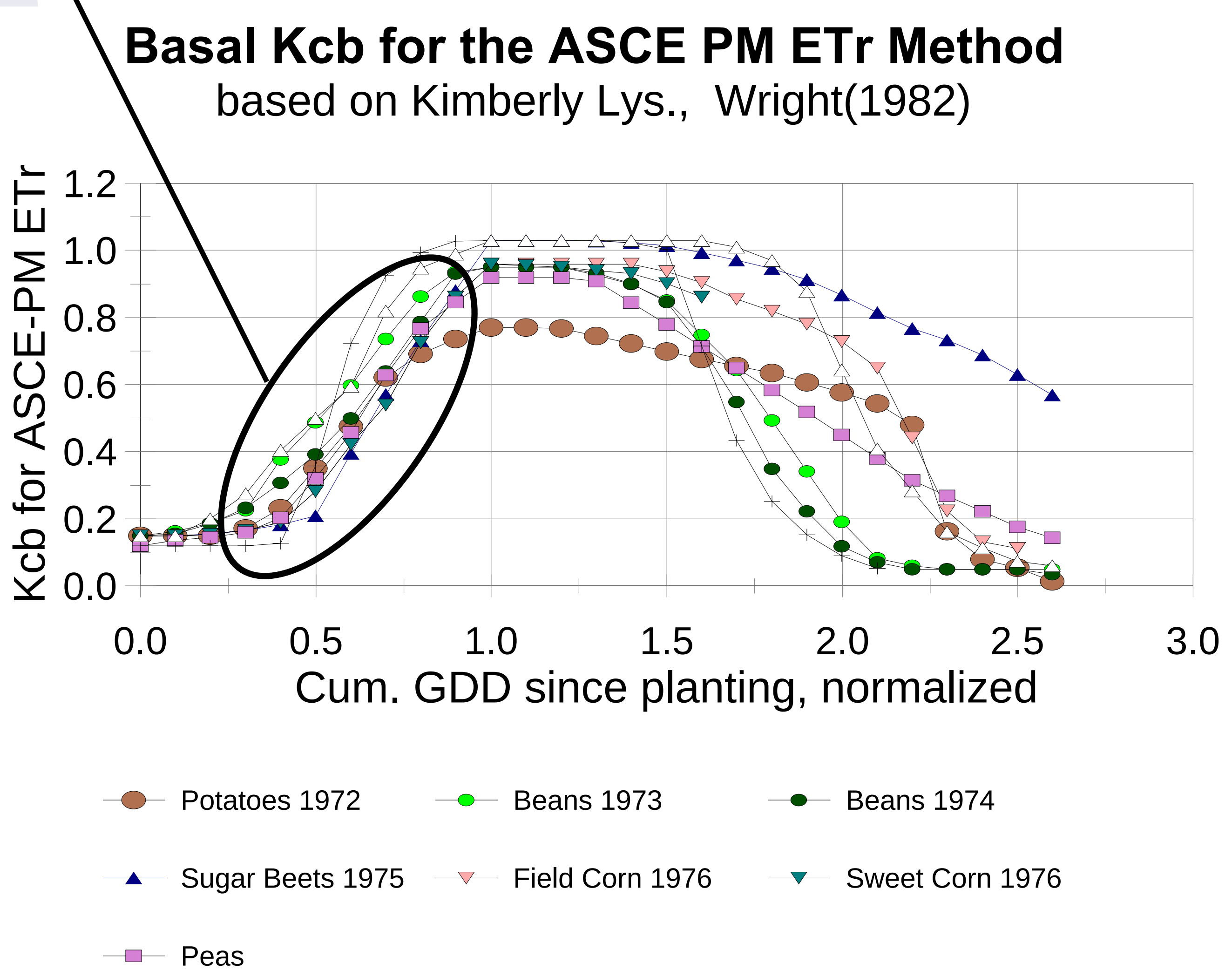
	Spr. Wht	Wint Wht	Peas seed	Peas frsh	Sug. Beet	Pot. bake	Pot. proc ess.	Bea ns	Field Corn
GDD Base, °C	0	0	0	0	5	5	5	5	10-corn
CGDD Planting to EFC	840	1080	635	635	970	740	700	670	540
CGDD Planting to Terminate	2160	2600	1620	1000	2600	1780	1500	950	1400

(winter wheat is planted Oct. 15 and accumulates all winter)

http://www.kimberly.uidaho.edu/ETIdaho/

CGDD creates some similarity in the K_{cb} shape

similar shapes during development vs. CGDD



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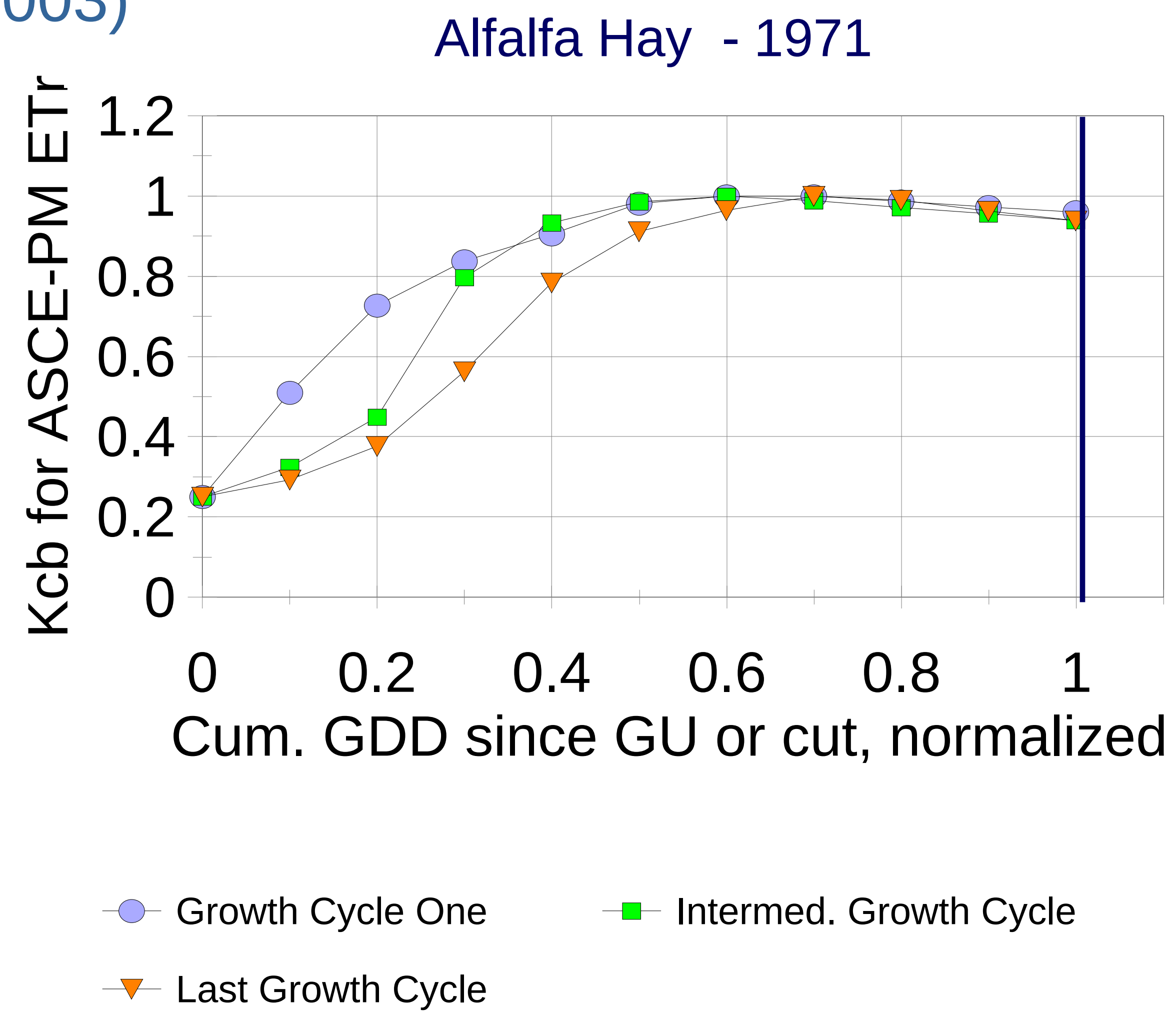


Cumulative GDD for Wright (1982) K_{cb}'s as used in Idaho – Allen and Robison (2007)

Alfalfa Hay

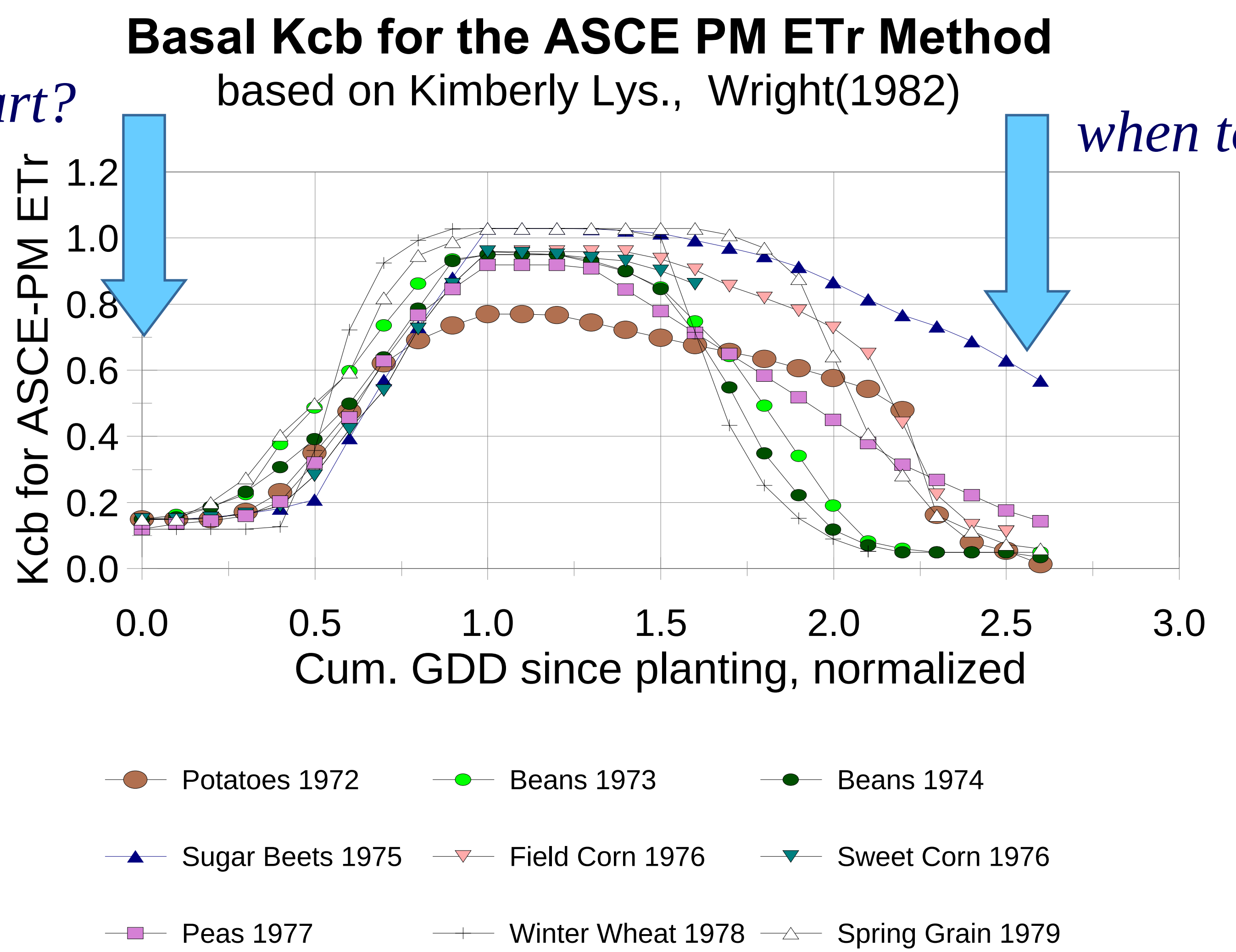
	First Period	Int. Per.	Last Per.
GDD Base, °C	0	0	
CGDD Start to Cut – Infrequent Cuttings	850	900	To k. frost
CGDD Start to Cut – Frequent Cuttings (dairy)	700	650	To k. Frost

http://www.kimberly.uidaho.edu/ETIdaho/

Starting and Ending the K_{cb}

when to start?

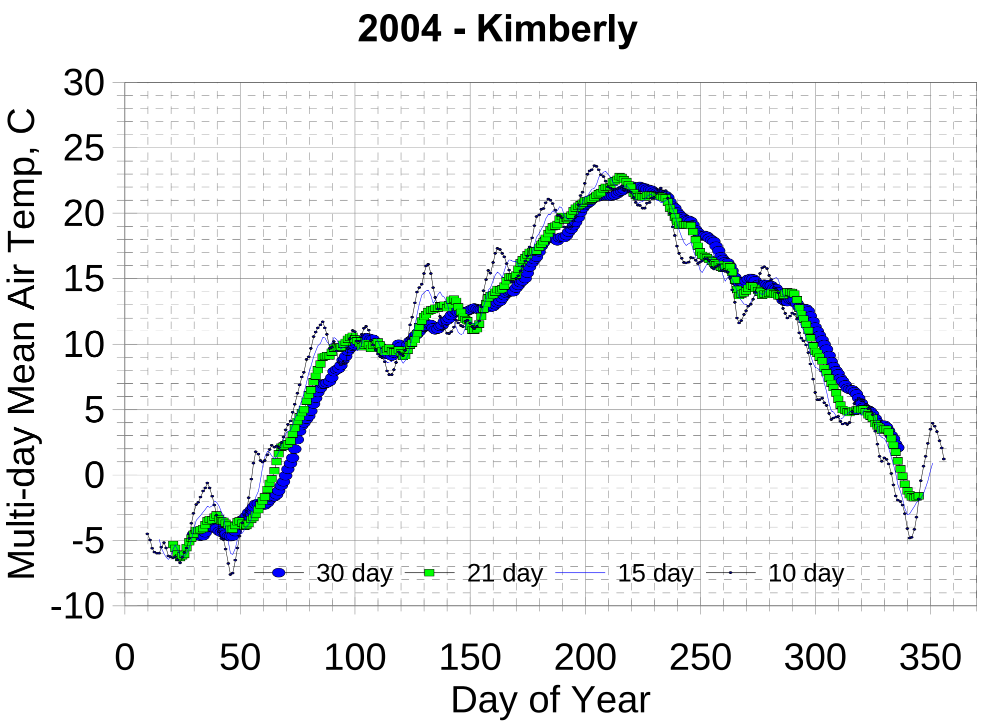
when to end?

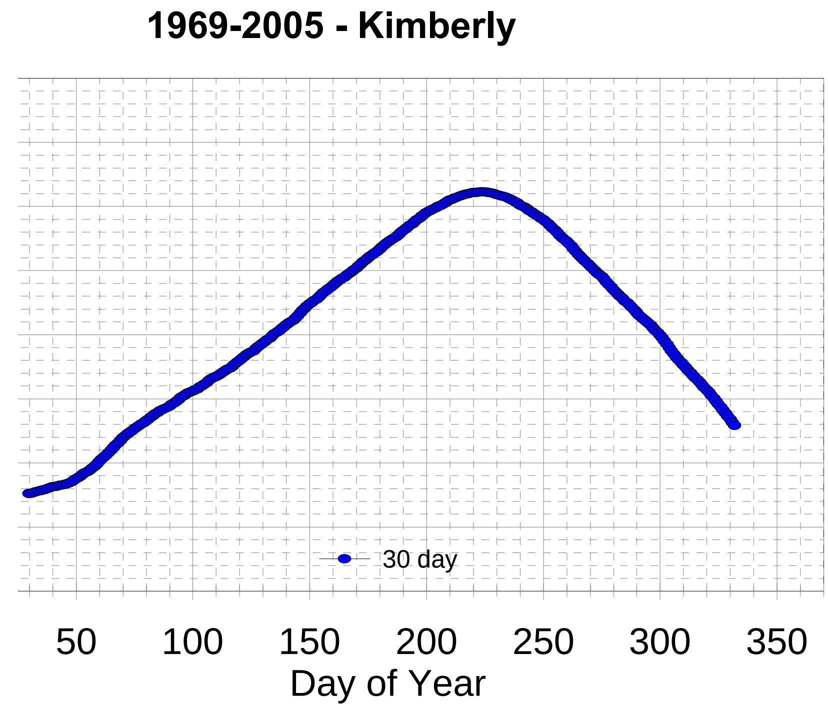


 http://www.kimberly.uidaho.edu/water/asceewri/Conversion_of_Wright_Kcs_2c.pdf

How to Start Planting or Greenup:

30 day (running average) mean daily air temperature





--similar to SCS method, except it is better to use T30 that <u>ENDS</u> on the predicted planting/greenup date

T_{30} for Idaho Crops – Allen and Robison (2007)

	Spr. Wht	Peas seed	Sug. Beet	Pot. bake	Field Corn	Bean s
Year of Wright	1979	1977	1975	1972	1976	1973
Plant Date of Wright	Apr 1	Apr 10	Apr 15	Apr 25	May 5	May 22
T30 used in ETIdaho, °C	4	5	8	6 to 7	10	14

http://www.kimberly.uidaho.edu/ETIdaho/

Cumulative GDD to Estimate Alfalfa Greenup – Allen and Robison (2007)

Cumulative growing degree days since January 1
for the date of greenup for alfalfa at Kimberly (*Ranger variety*)

Year	0^o base	Actual Green up
1969	200	4/03
1970	240	3/15
1971	240	4/05

240 GDD is used in Idaho

http://www.kimberly.uidaho.edu/ETIdaho/

When to End: Killing Frosts

Killing Frosts as used in Idaho – Allen and Robison (2007) (^{o}C)

Spr. Wht	Peas seed	Sug. Beet	Pot. bake	Field Corn	Bean	Alf alfa	Past.	Hops
---	-4	-4	-2	-4 to -5	-2	-7	-5	-2

Cattails	Poplar	Cotton wood	Willows	Sun flowr
-2	-5	-4	-6	-4

--Note: These are temperatures inside a Weather Shelter *(not on the ground)*

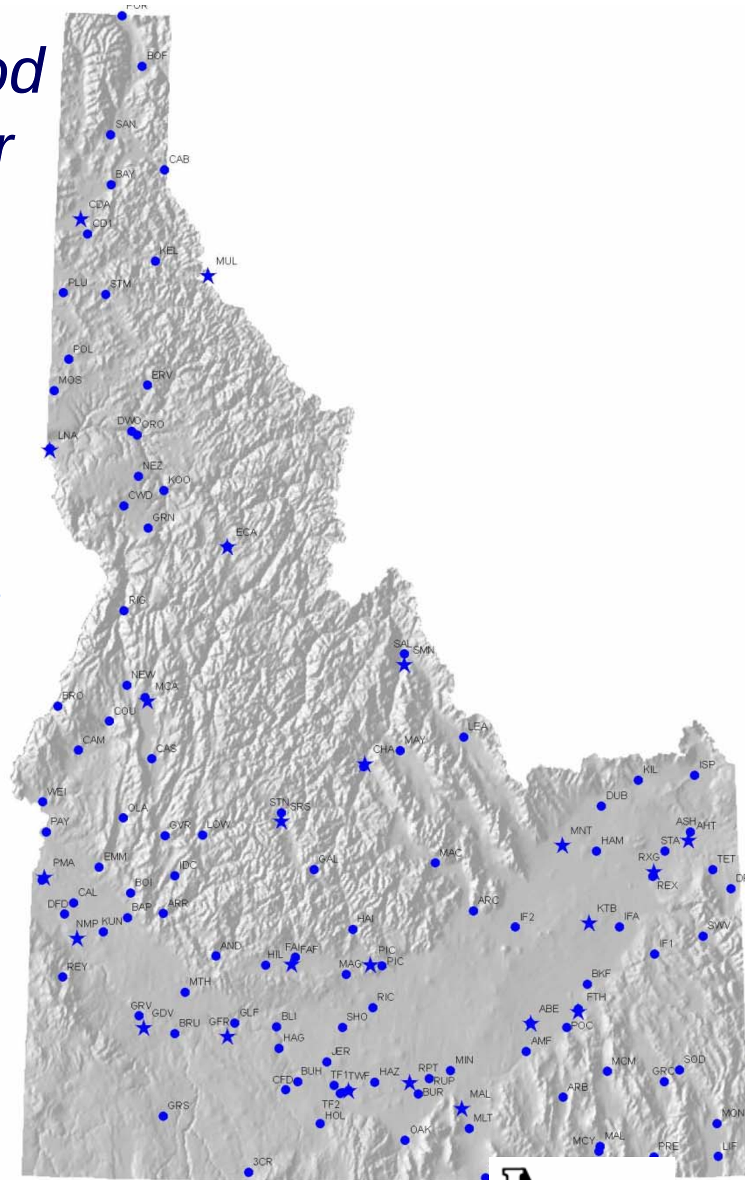
http://www.kimberly.uidaho.edu/ETIdaho/

Applying the Dual K_c method for Assessment of Water Resources Depletion

- Advantages
  - K_c value varies with wetting frequencies
  - K_c estimates can be made during wintertime when process is evaporation from soil

The Dual K_c x ASCE PM Method is now the <u>Preferred Method</u> for water transfers and administration in Idaho (Spackman memo 2008 Idaho Dept. Water Resources)

Evapotranspiration and Consumptive Irrigation Water Requirements for Idaho



R.G. Allen and C.W. Robison (2007, 2009)

http://www.kimberly.uidaho.edu/ETIdaho/

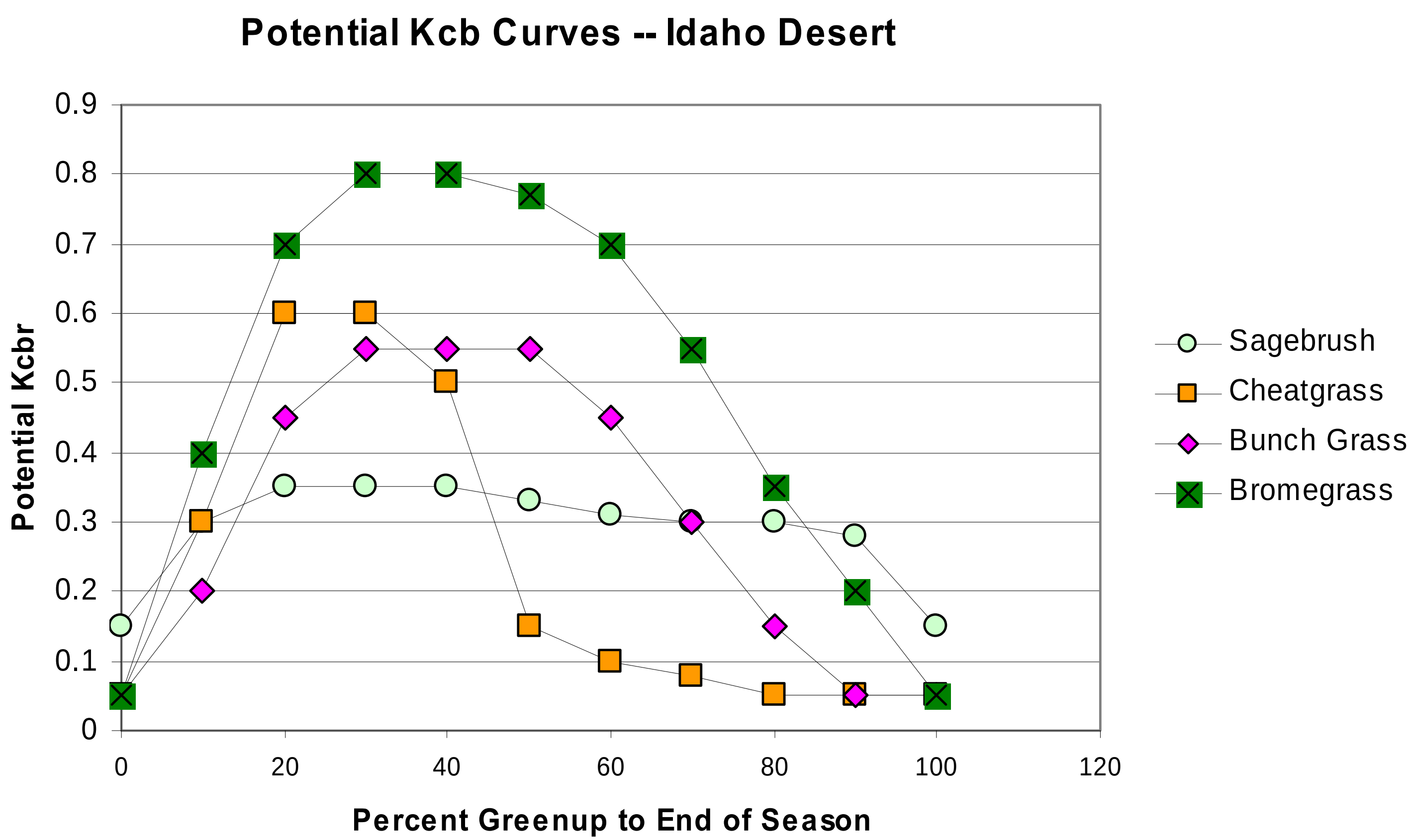
(Google for “ETIdaho” →www.kimberly.uidaho.edu/ETIdaho/)

Dual K_c-based ET for Idaho

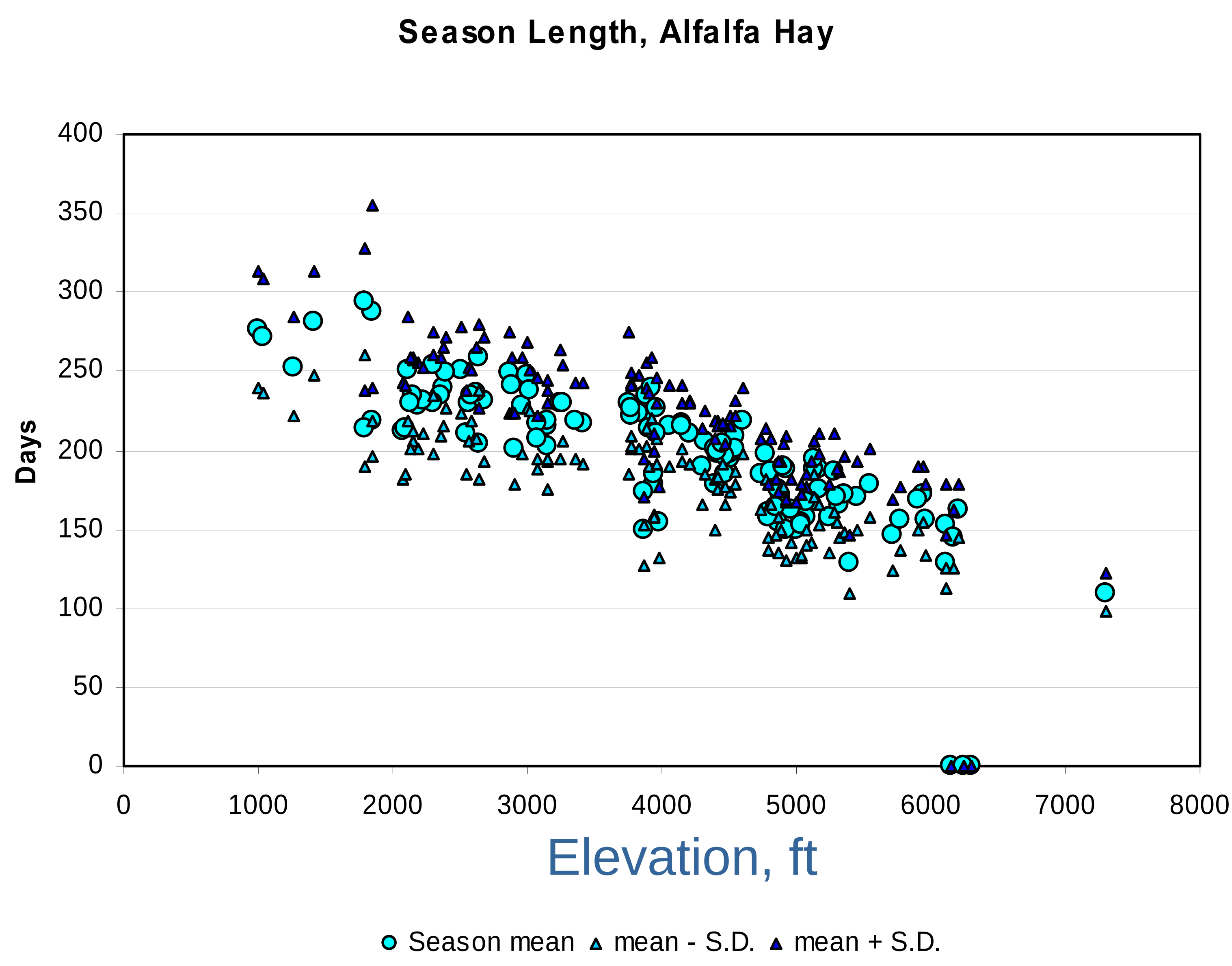
- Estimates are made “24/7” at 132 locations
  - 365 days per year
    - growing and <u>nongrowing</u> seasons
    - > 30 crops + 12 non.ag.crops + 3 open water classes
  - provide daily estimates of evaporation from soil during winter *(for hydrologic impacts and Eff.Prec.)*
- Crop planting and season length are dynamic *(function of weather)*
- Estimates run for more than 100 years
  - *Based on daily T_{max} and T_{min} with:*
  - $T_{dew} = T_{min} - K_o$
  - *Solar Radation = $f(T_{max} - T_{min})$ -- (Thornton-Running)*
  - *Wind Speed = Long-term monthly averages*
- Plus 16 Agrimet stations that have full data

K_c's for Desert Vegetation

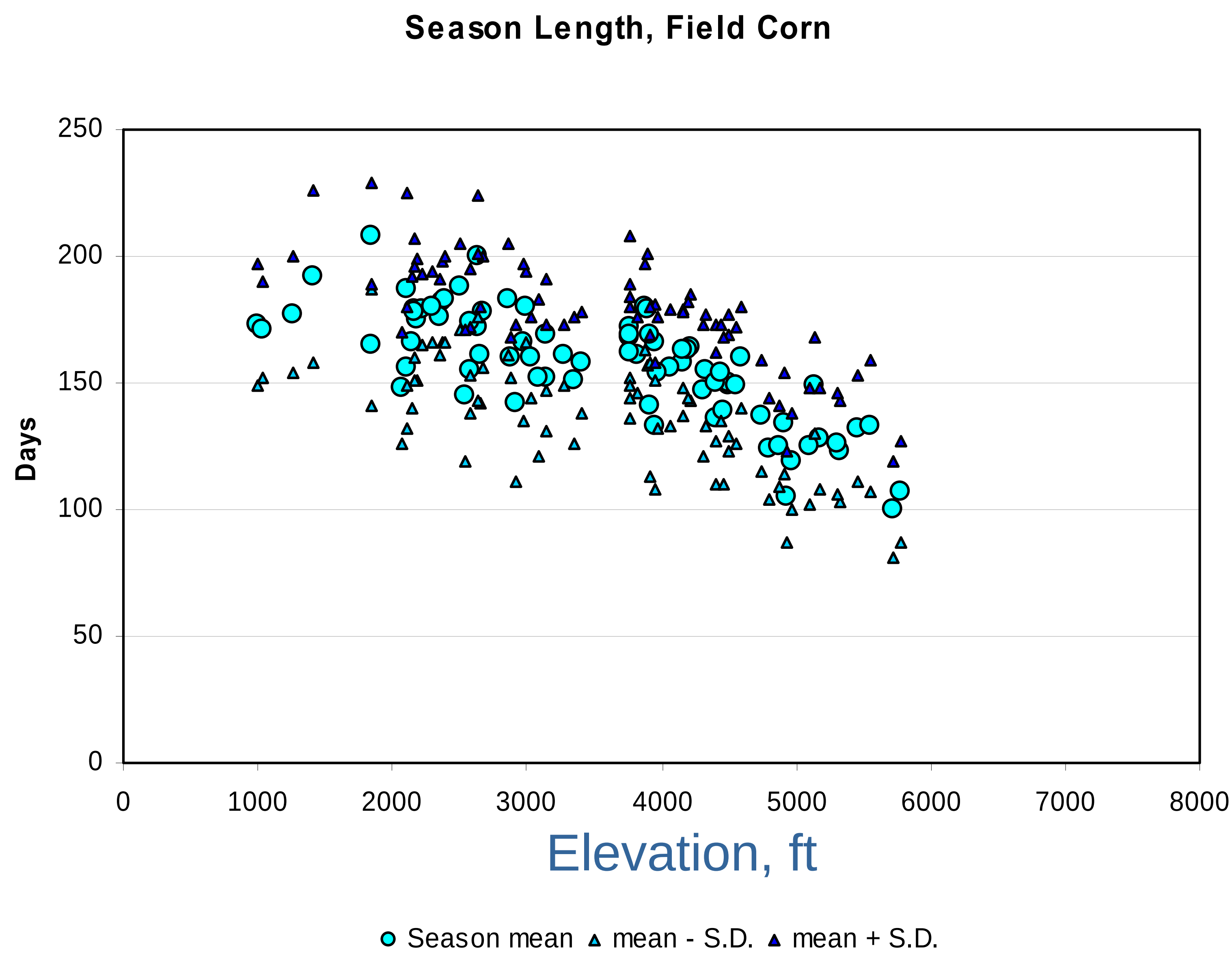
- potential K_{cb} from METRIC Satellite Estimates
- K_{cb} was reduced via stress coefficient/daily water balance



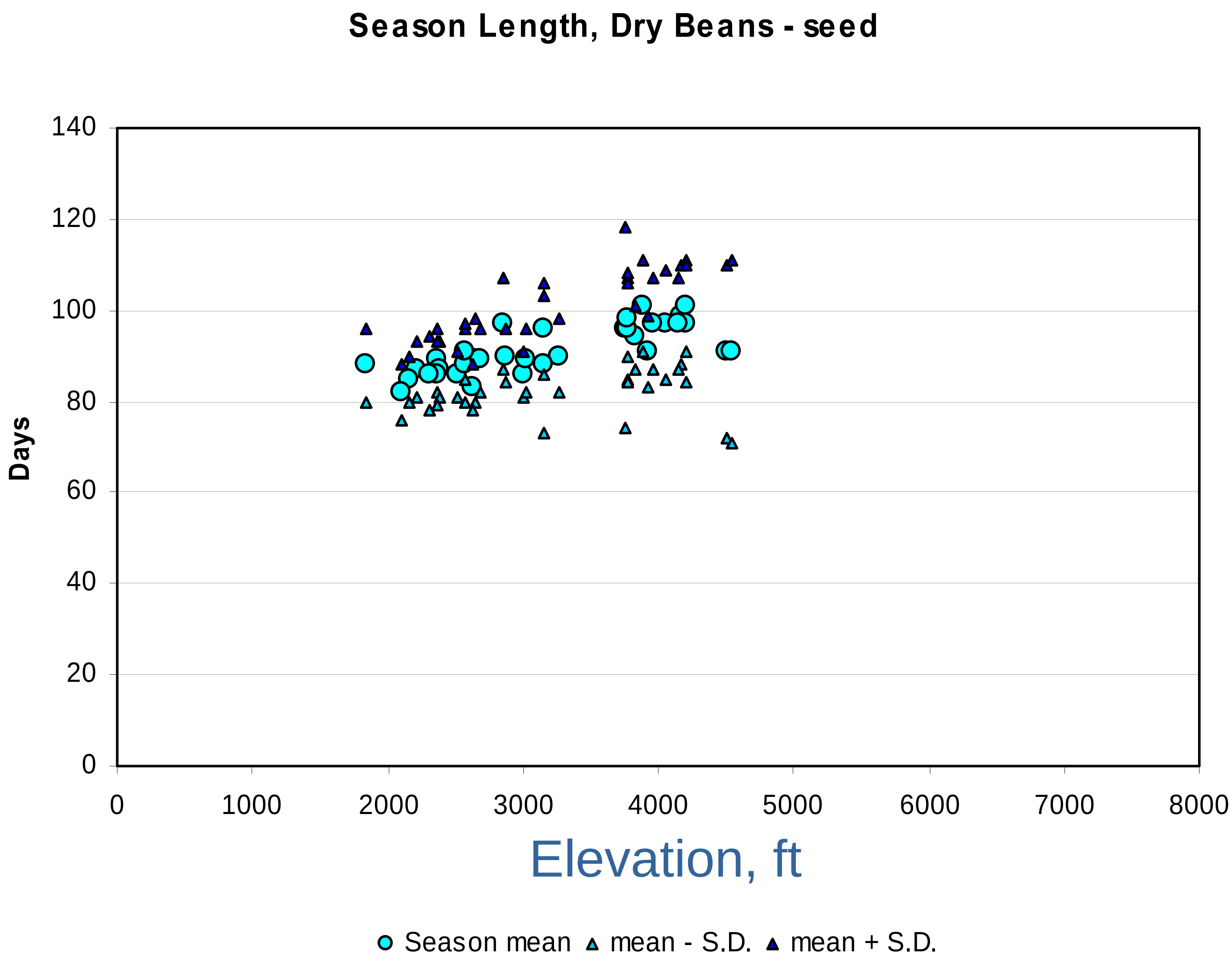
Alfalfa Season Lengths vs. Elevation across Idaho Thermal-estimated Start and Frost Ended



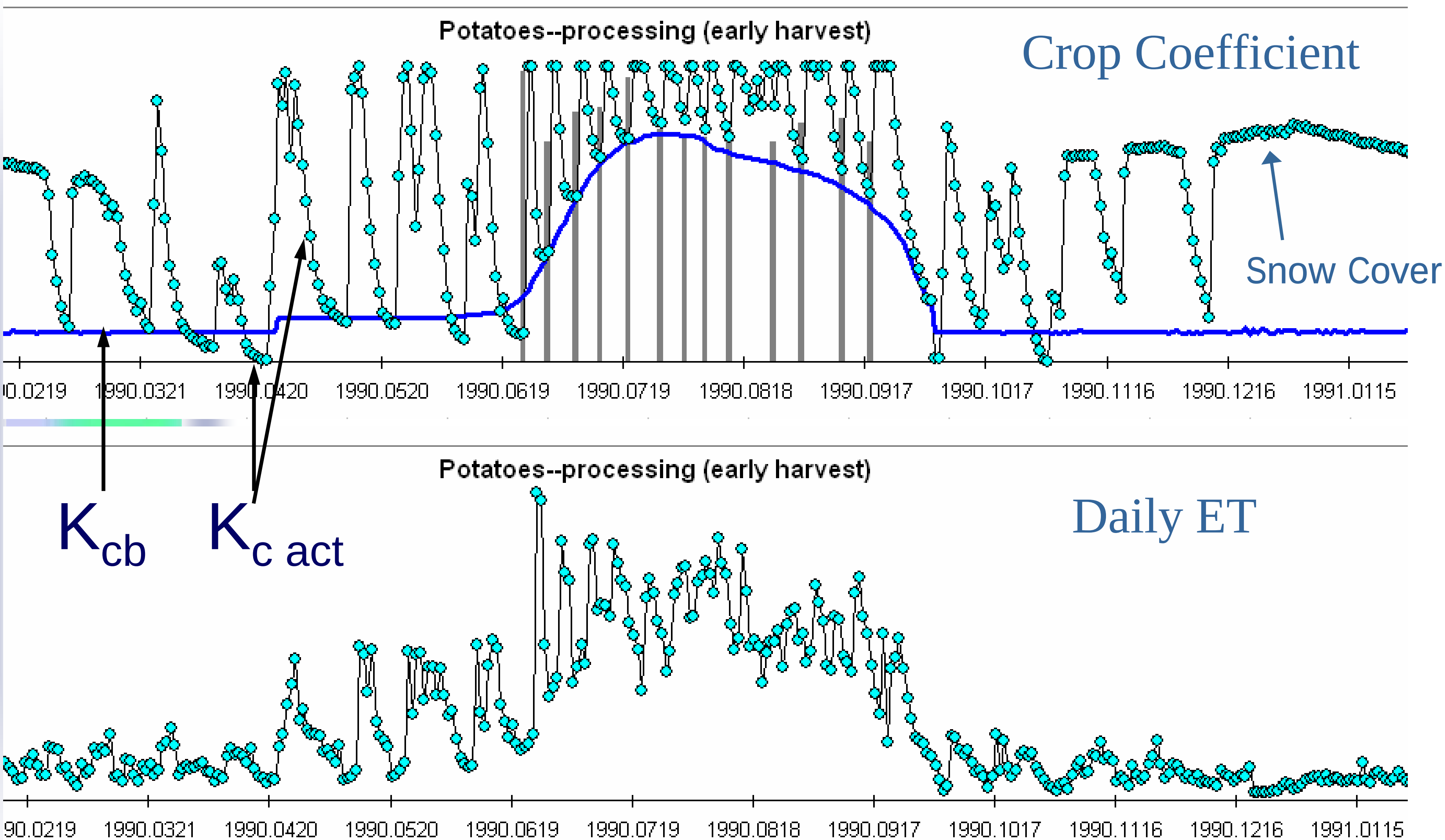
Defined **Field Corn** Season Lengths vs. Elevation Thermal-estimated Start and Thermal/Frost End



Defined **Dry Bean** Season Lengths vs. Elevation Thermal-estimated Start and Thermal-estimated End

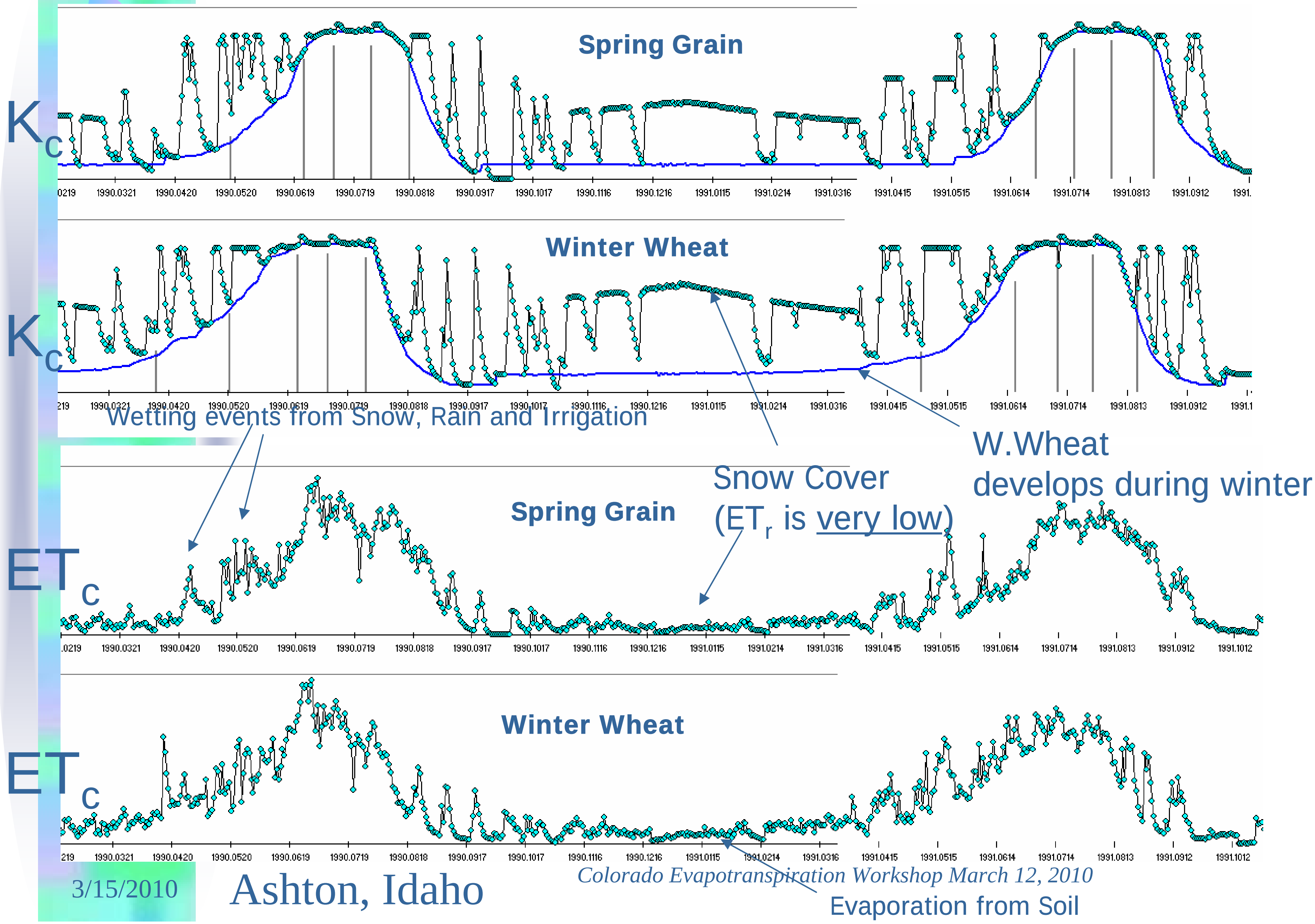


Ashton, 1990 calendar year -- Potatoes



$$K_{c\ act} = \left(K_s\ K_{cb} + K_e\right)\ \left(\ and\ \ ET_{c\ act} = K_{c\ act}\ \ ET_r\ \right)$$

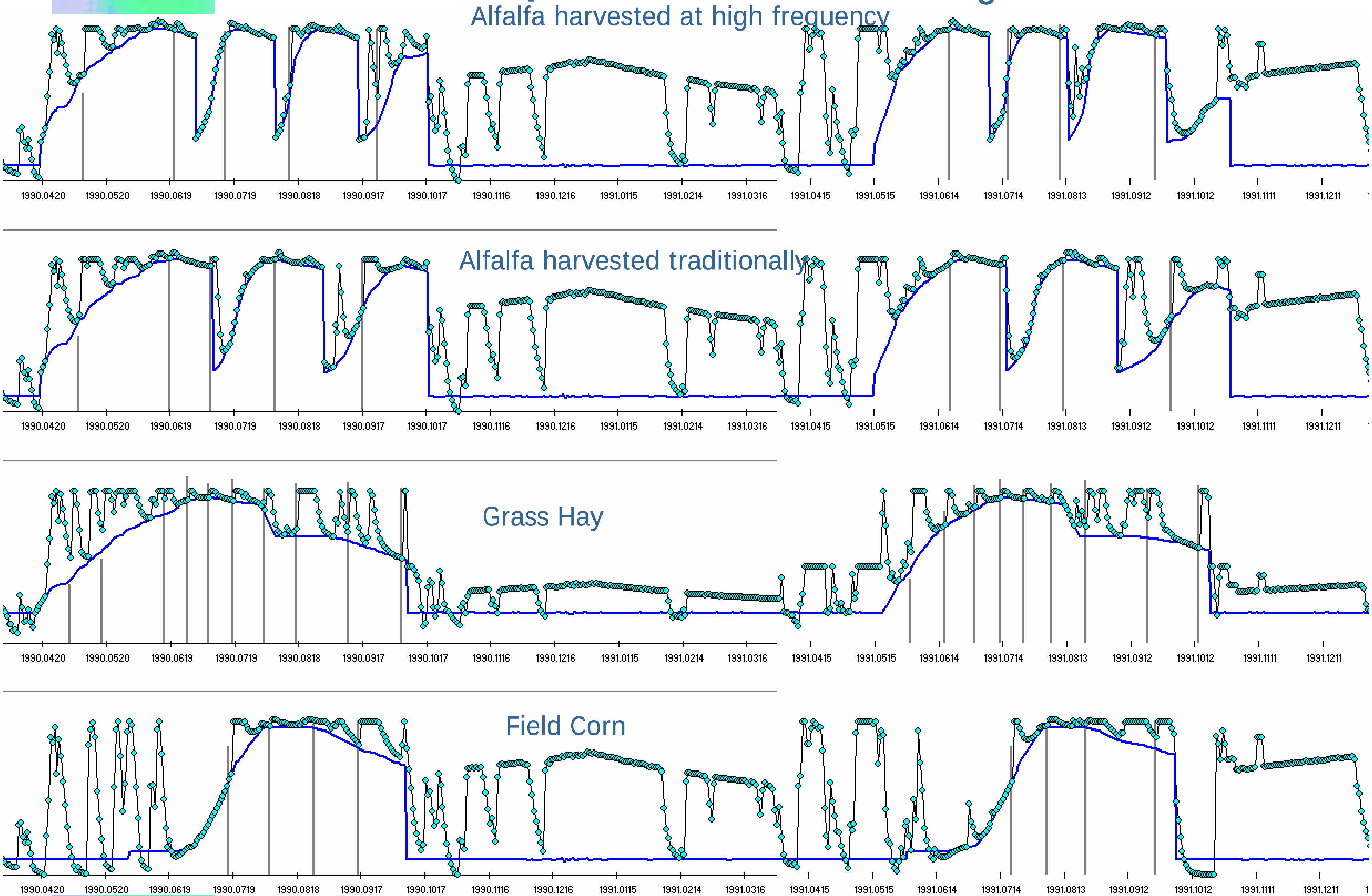
$$K_{c\ act} = \left(K_s\ K_{cb} + K_e\right) \qquad (\ and\ \ ET_{c\ act} = K_{c\ act}\ \ ET_r\ )$$



Ashton, Idaho

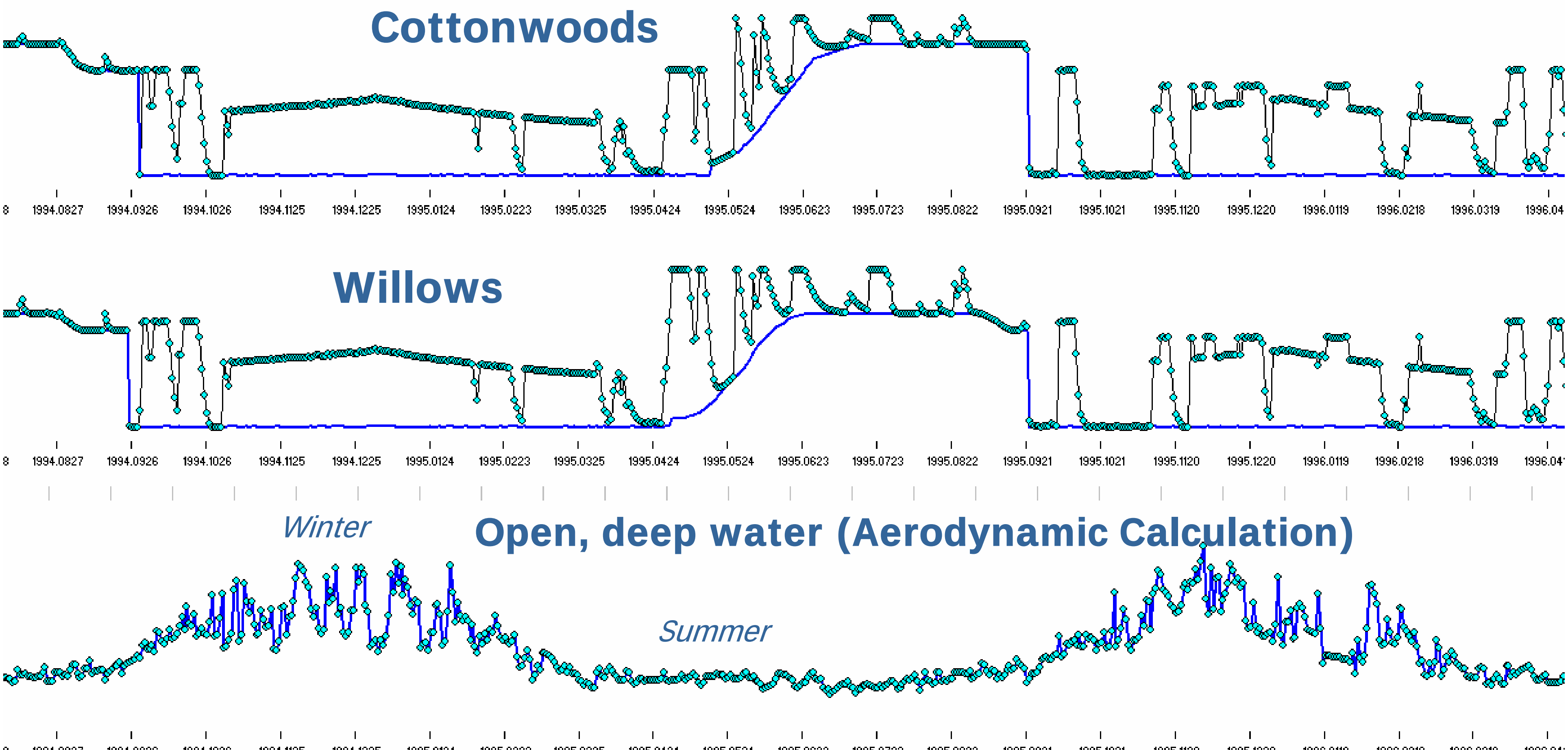
Ashton

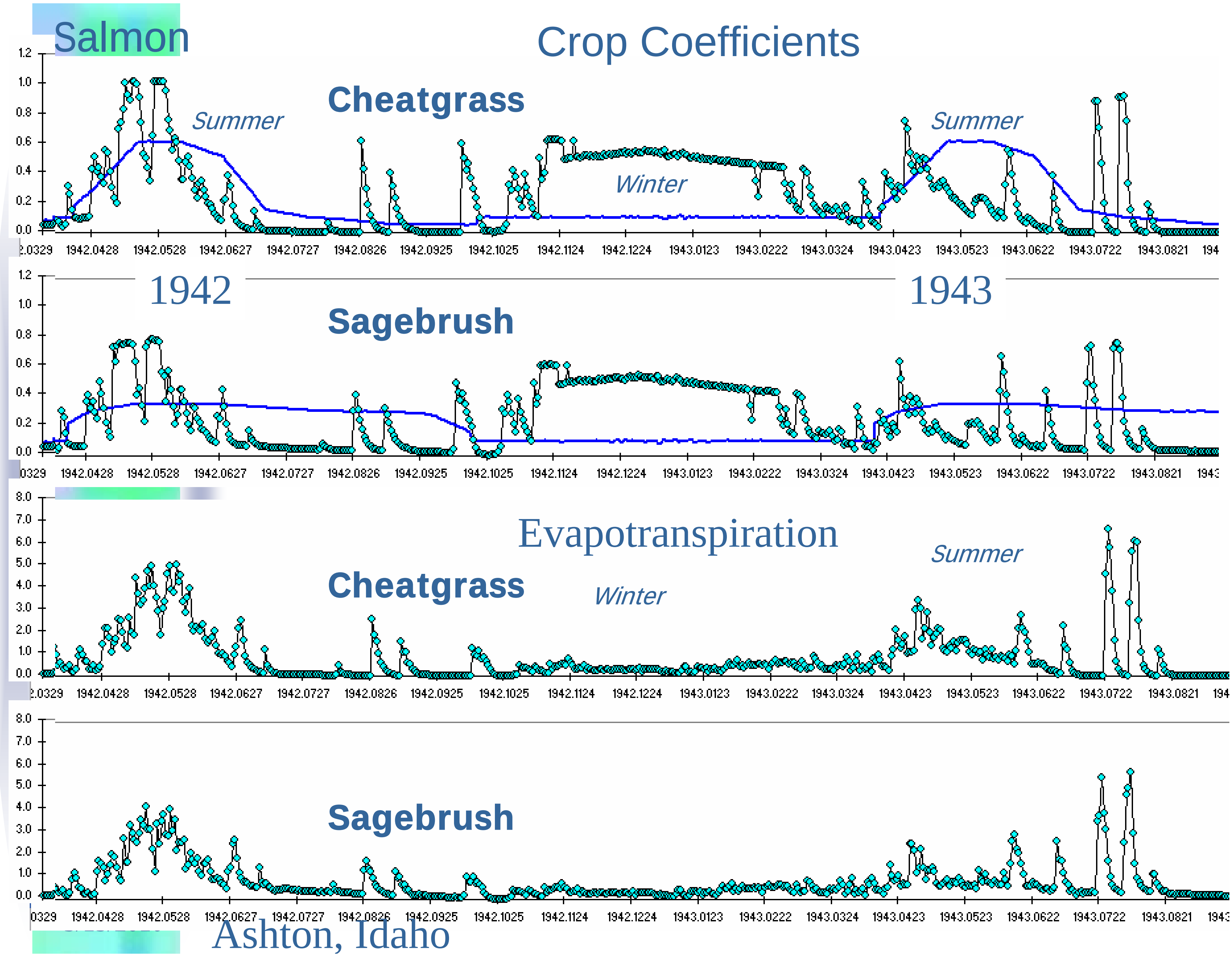
Crop Coefficients, K_c



Ashton

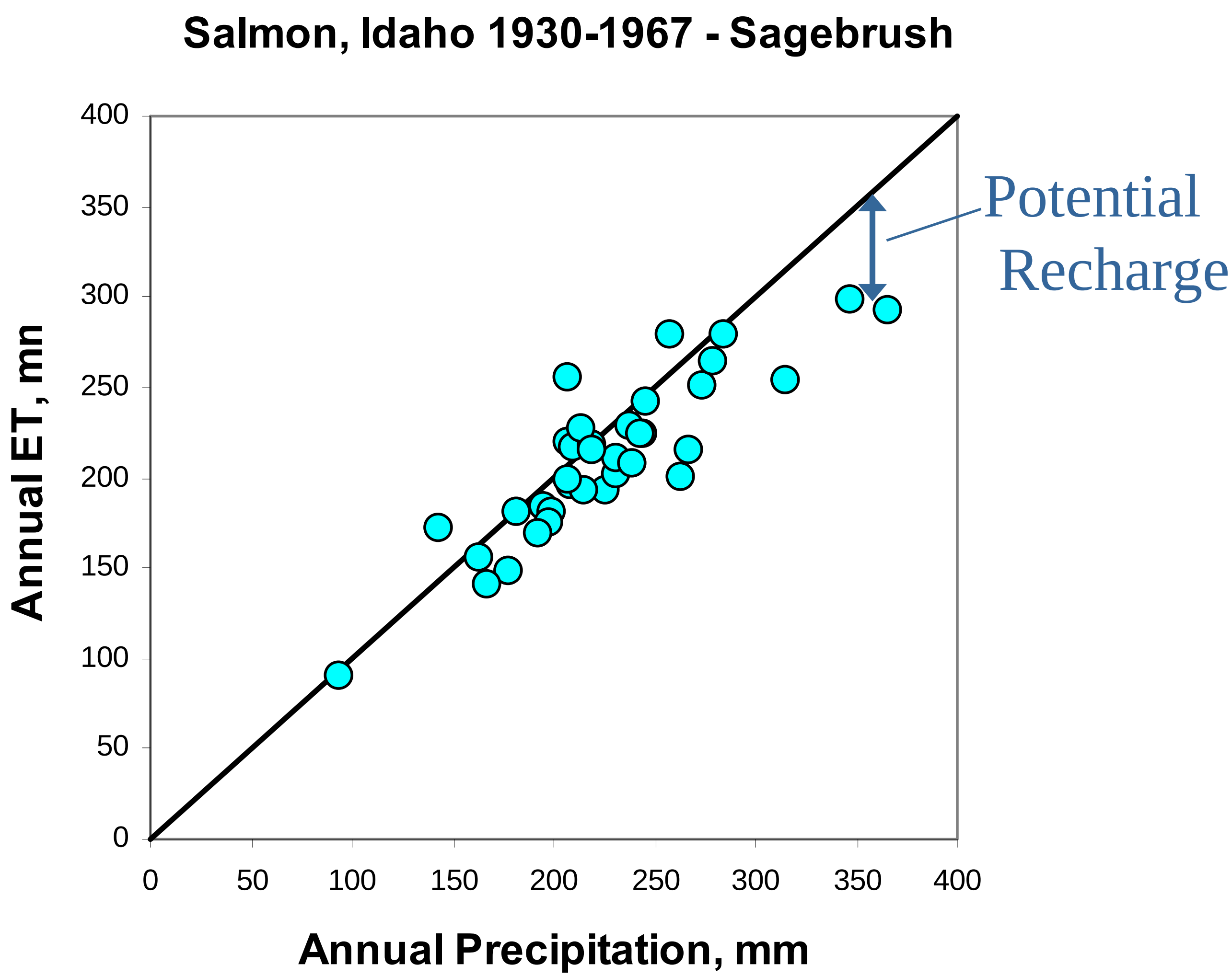
Crop Coefficients, K_c



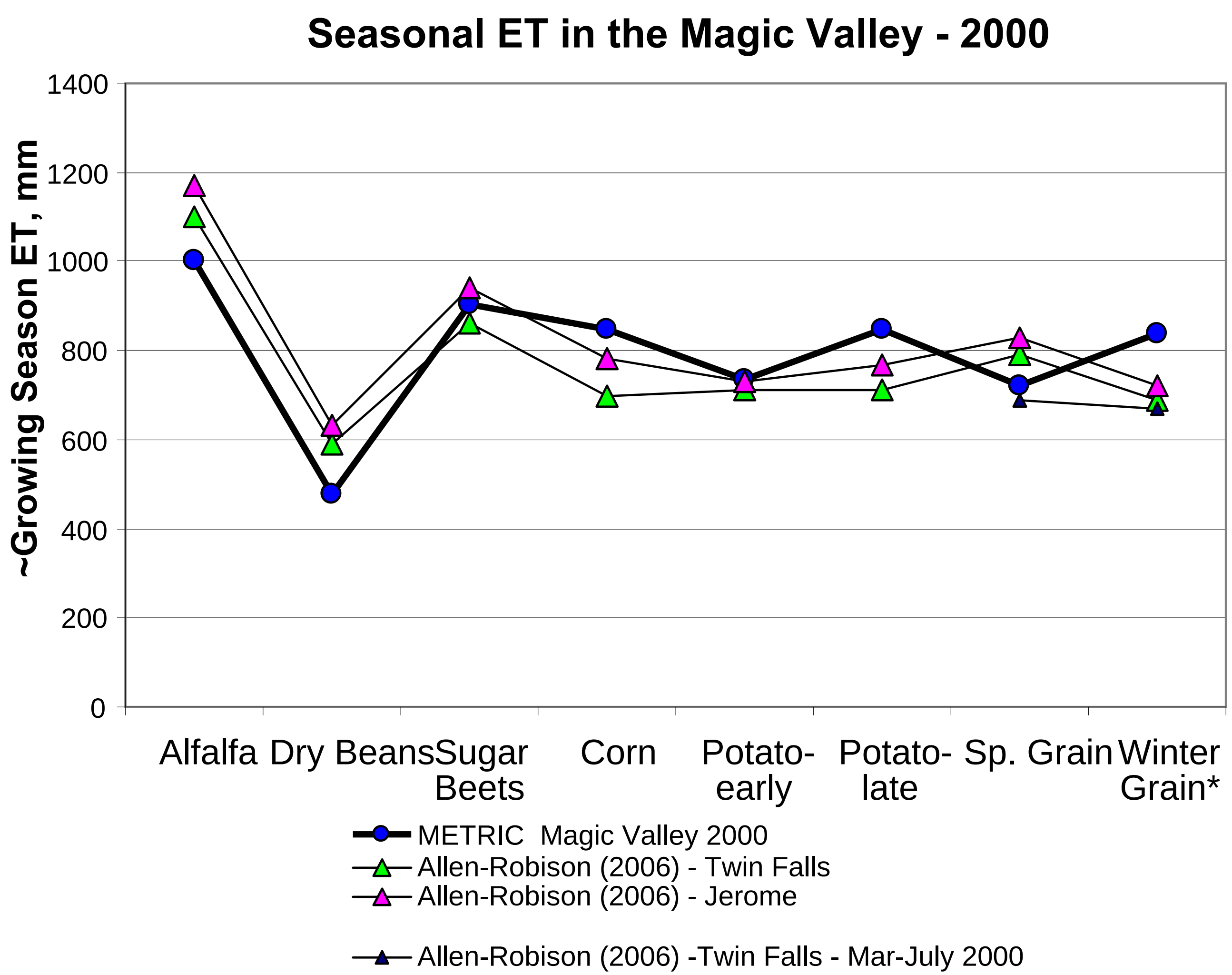


Salmon
Crop Coefficients
Cheatgrass
Summer
Winter
Summer
1942
1943
Sagebrush
Evapotranspiration
Cheatgrass
Winter
Summer
Sagebrush
Ashton, Idaho

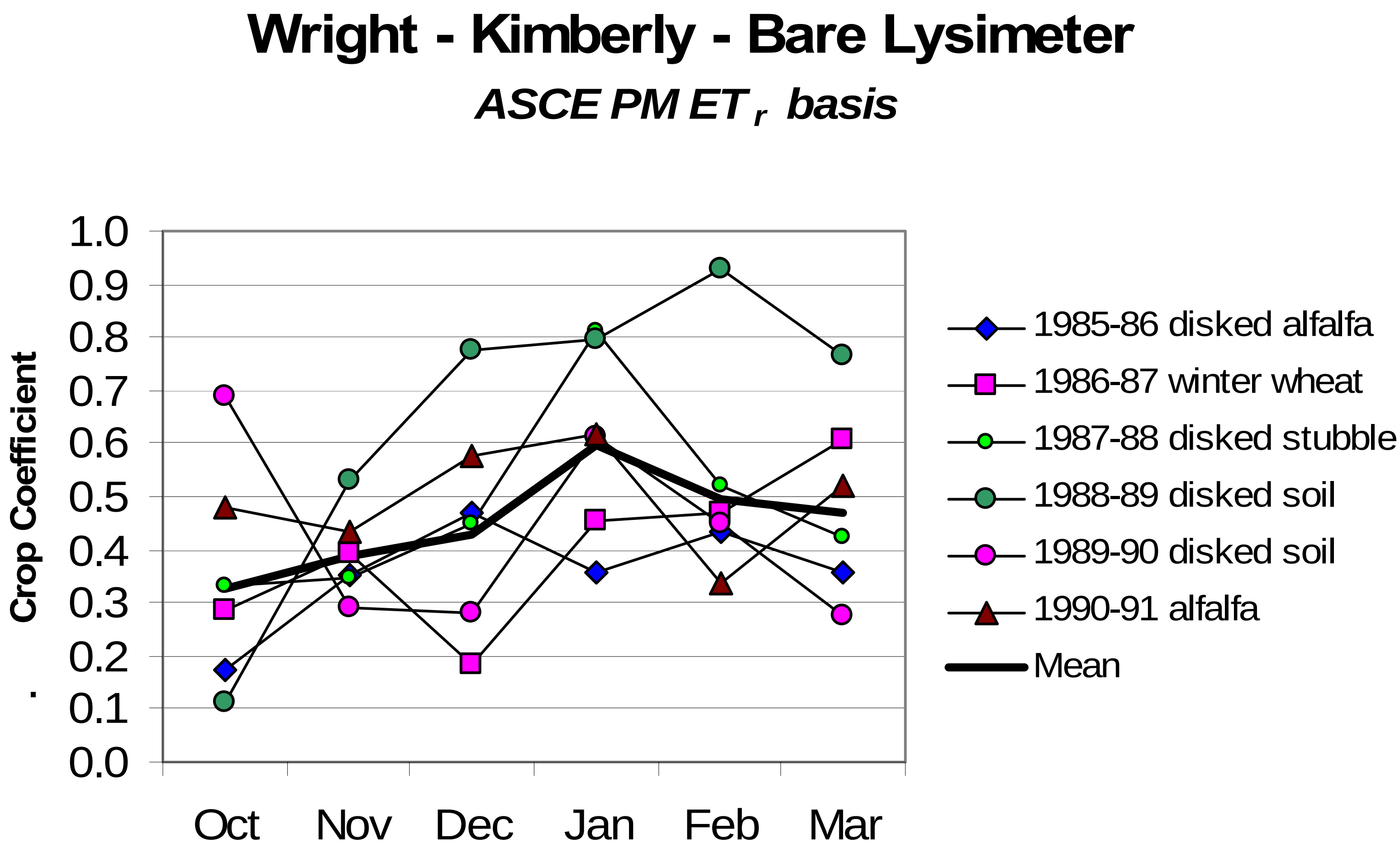
Annual ET vs. Precipitation



Comparison of Dual K_c method with Satellite-based Energy Balance (METRIC)

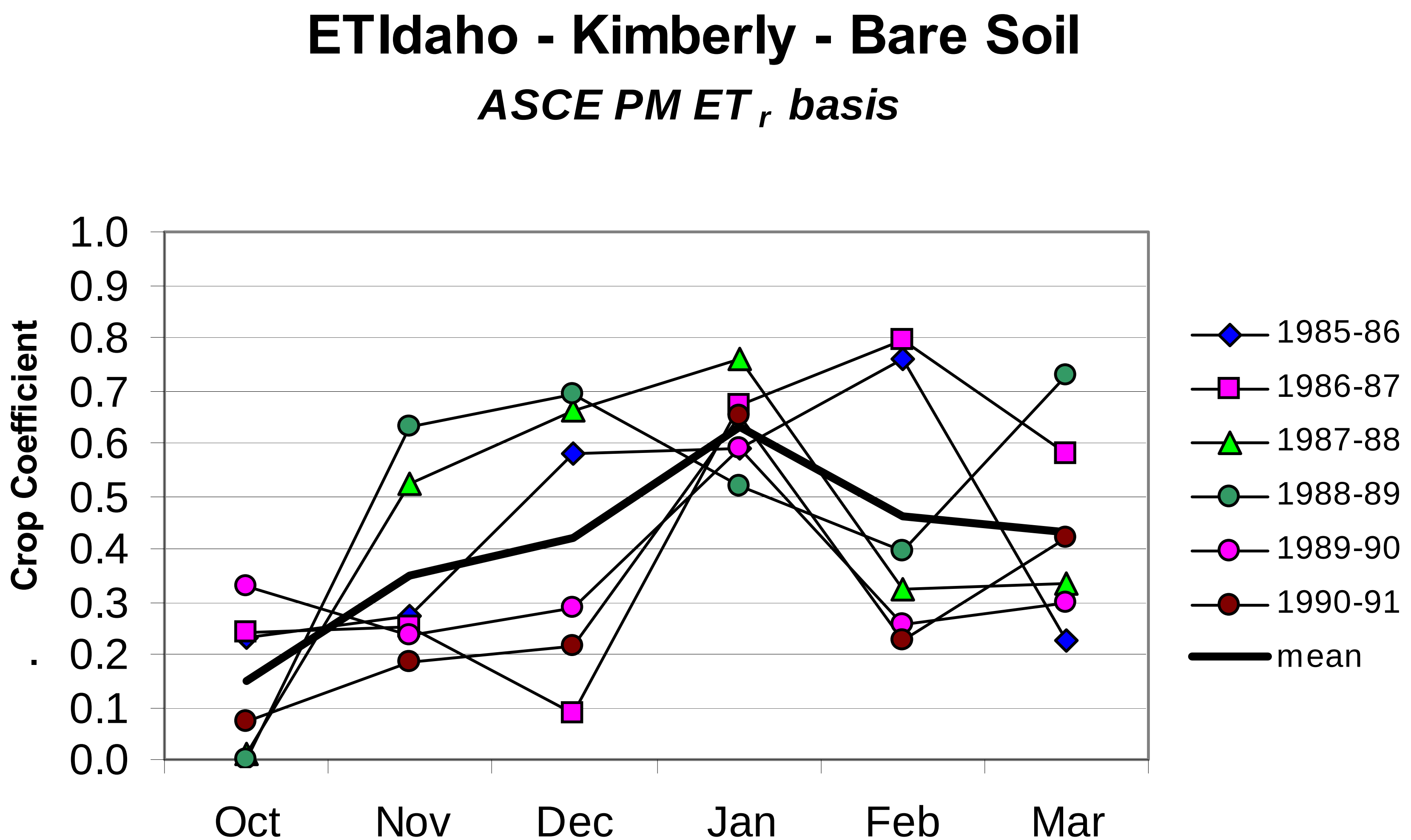


Wright Wintertime K_c --Kimberly, Idaho

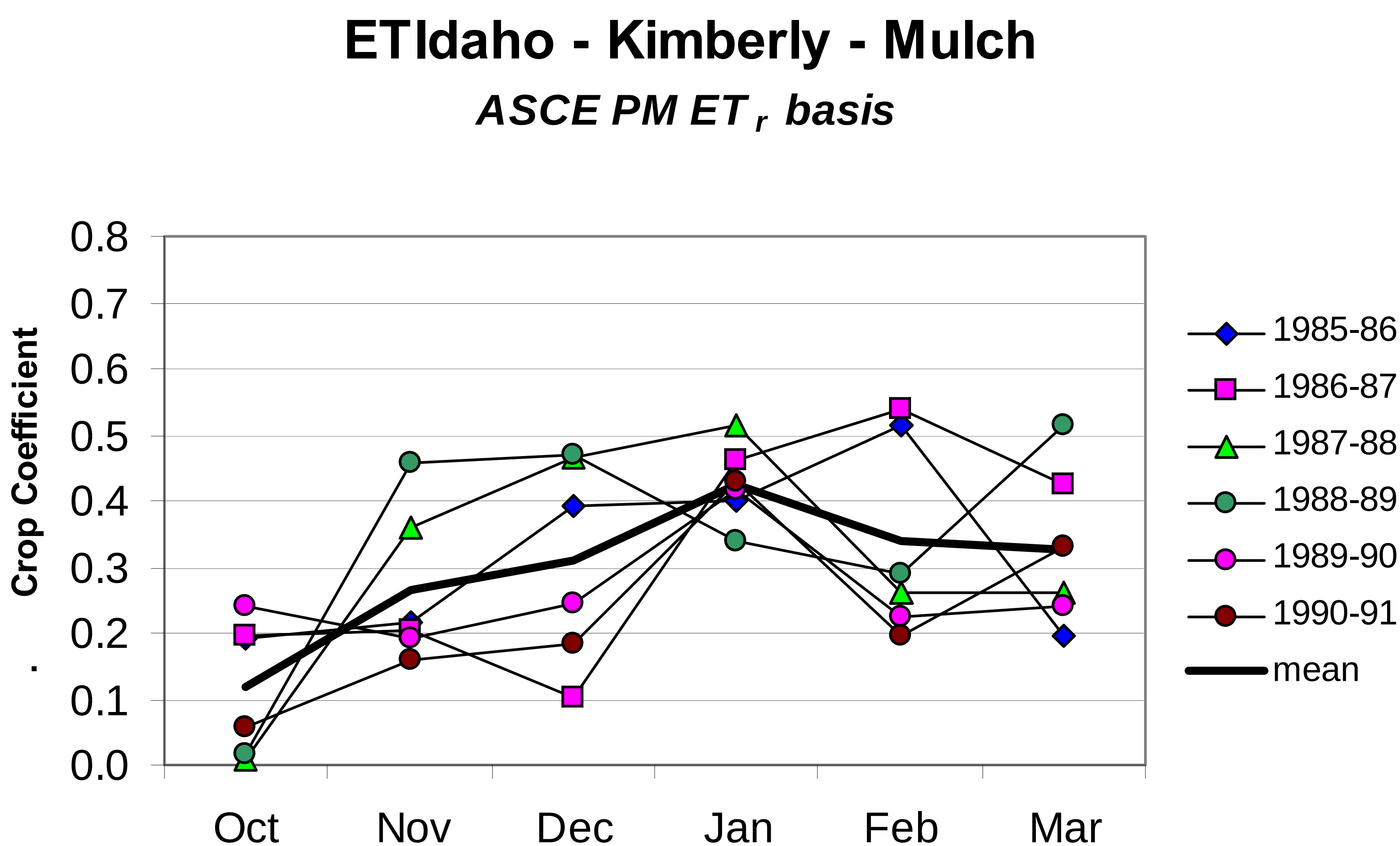


(Precipitation only. With water application, K_c is expected to increase)

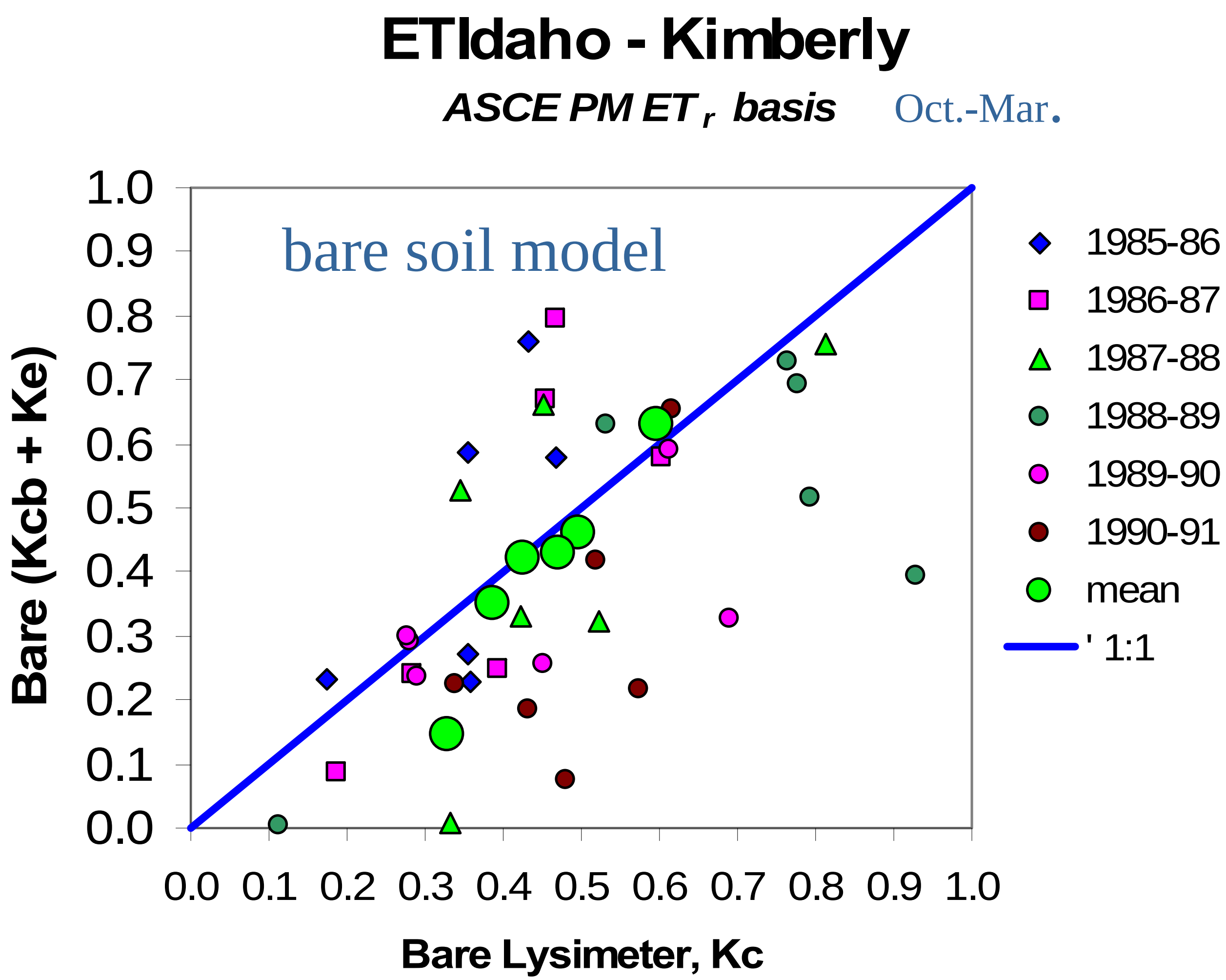
Nongrowing Season K_c Simulated using daily K_e model



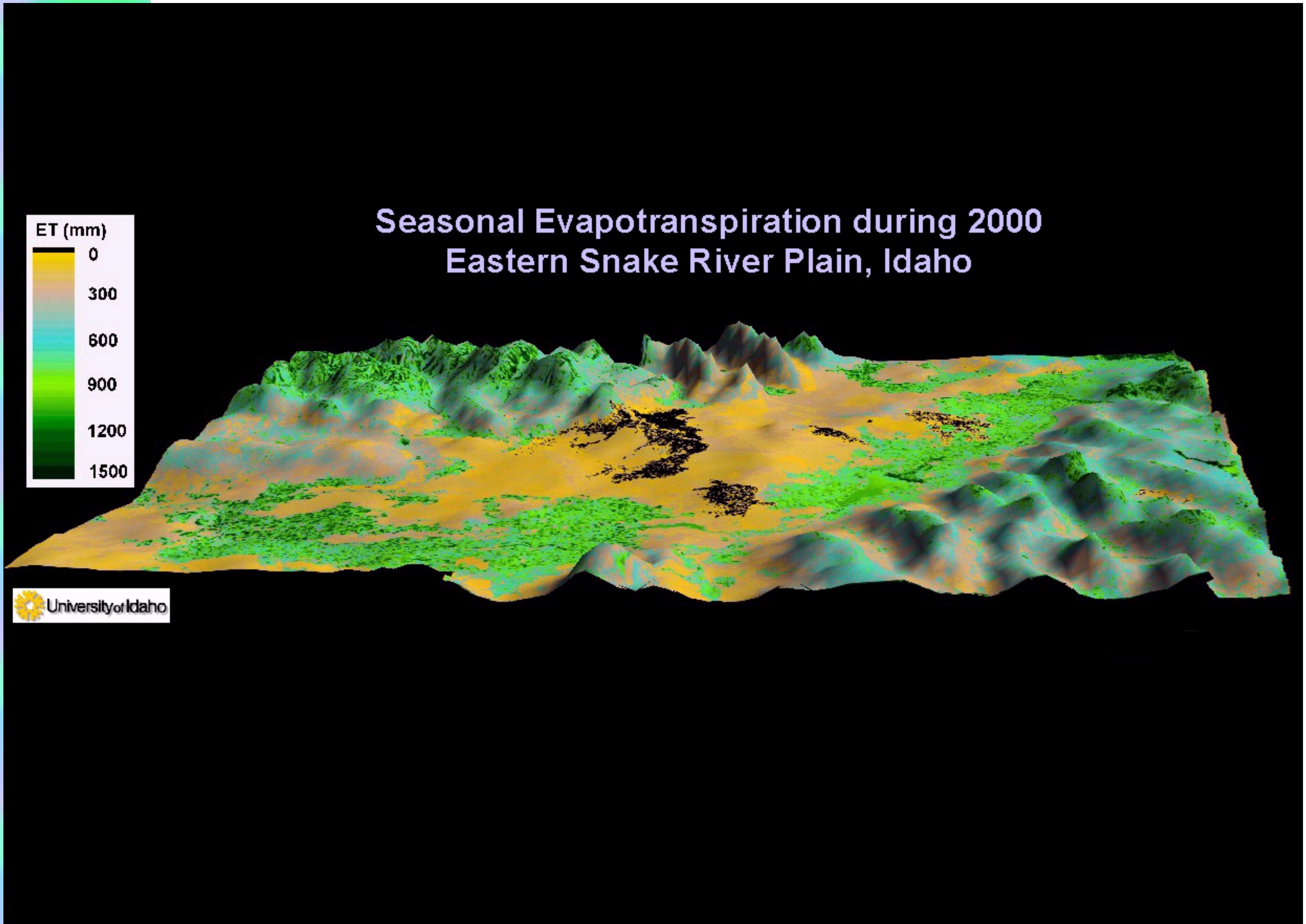
Nongrowing Season K_c Simulated using daily K_e model



Comparison of Monthly ET with Lysimeter

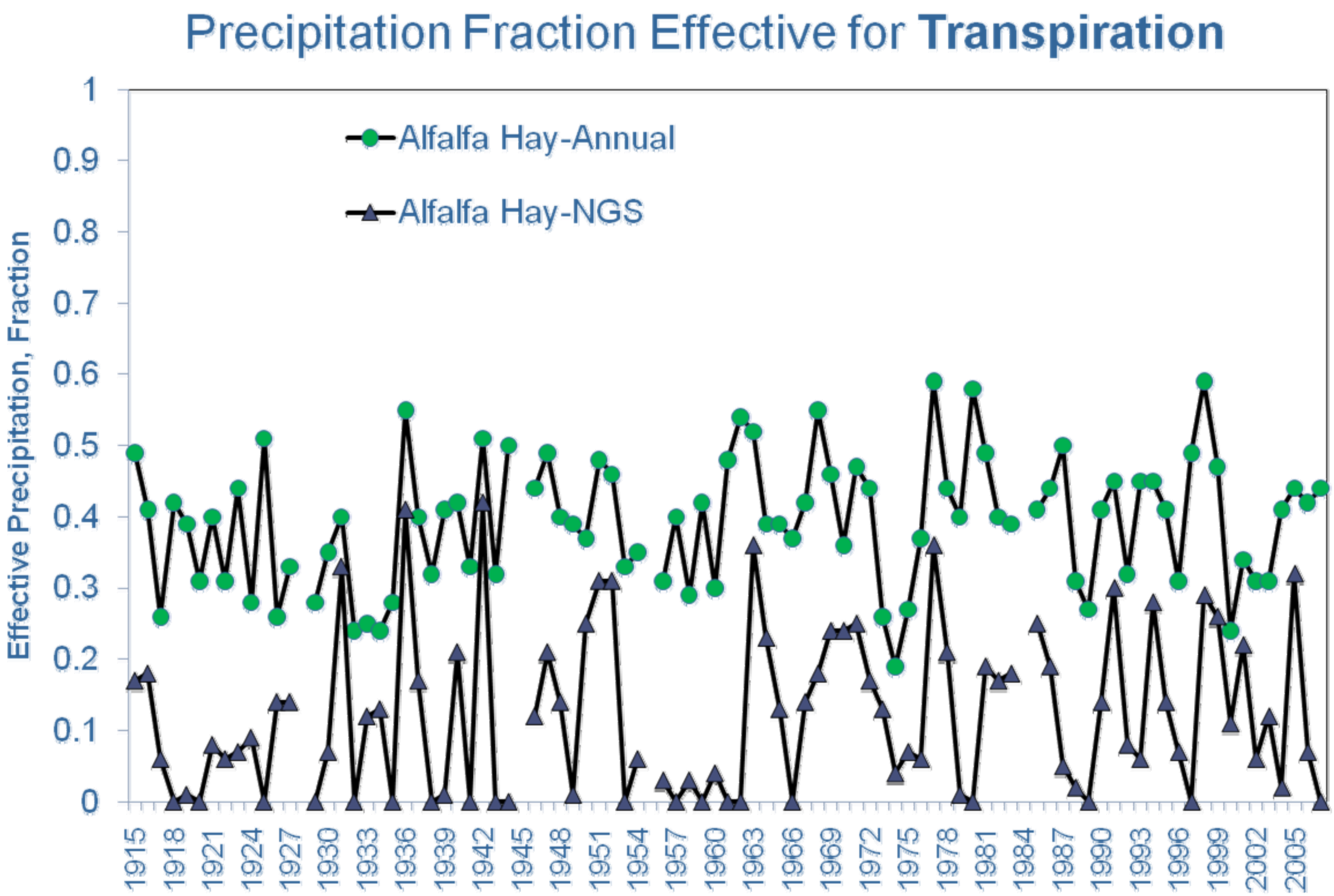


Uses of Satellite-based ET to Confirm/Refine K_c's

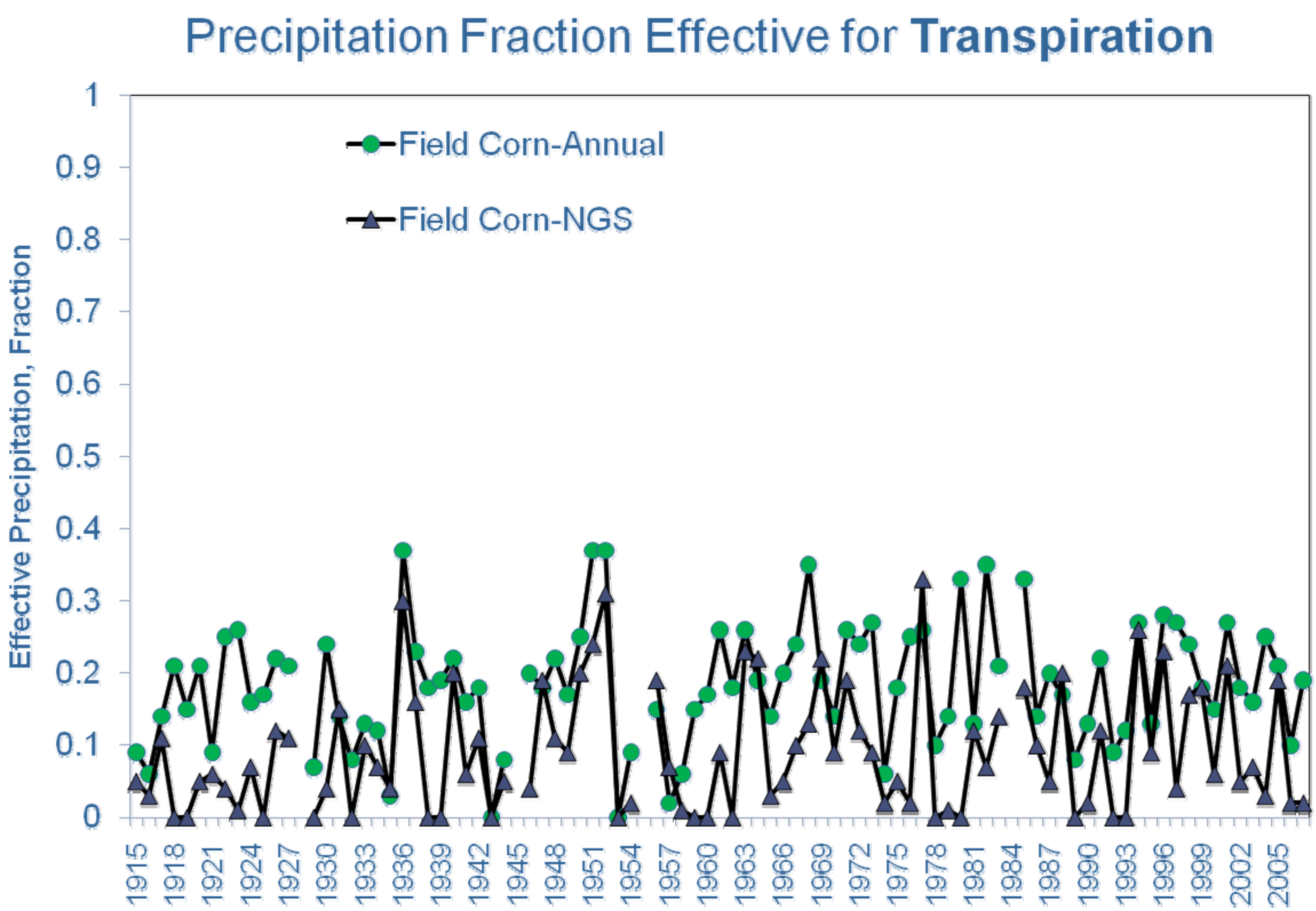


Seasonal ET from METRIC and Landsat (100 mile x 200 mile area)

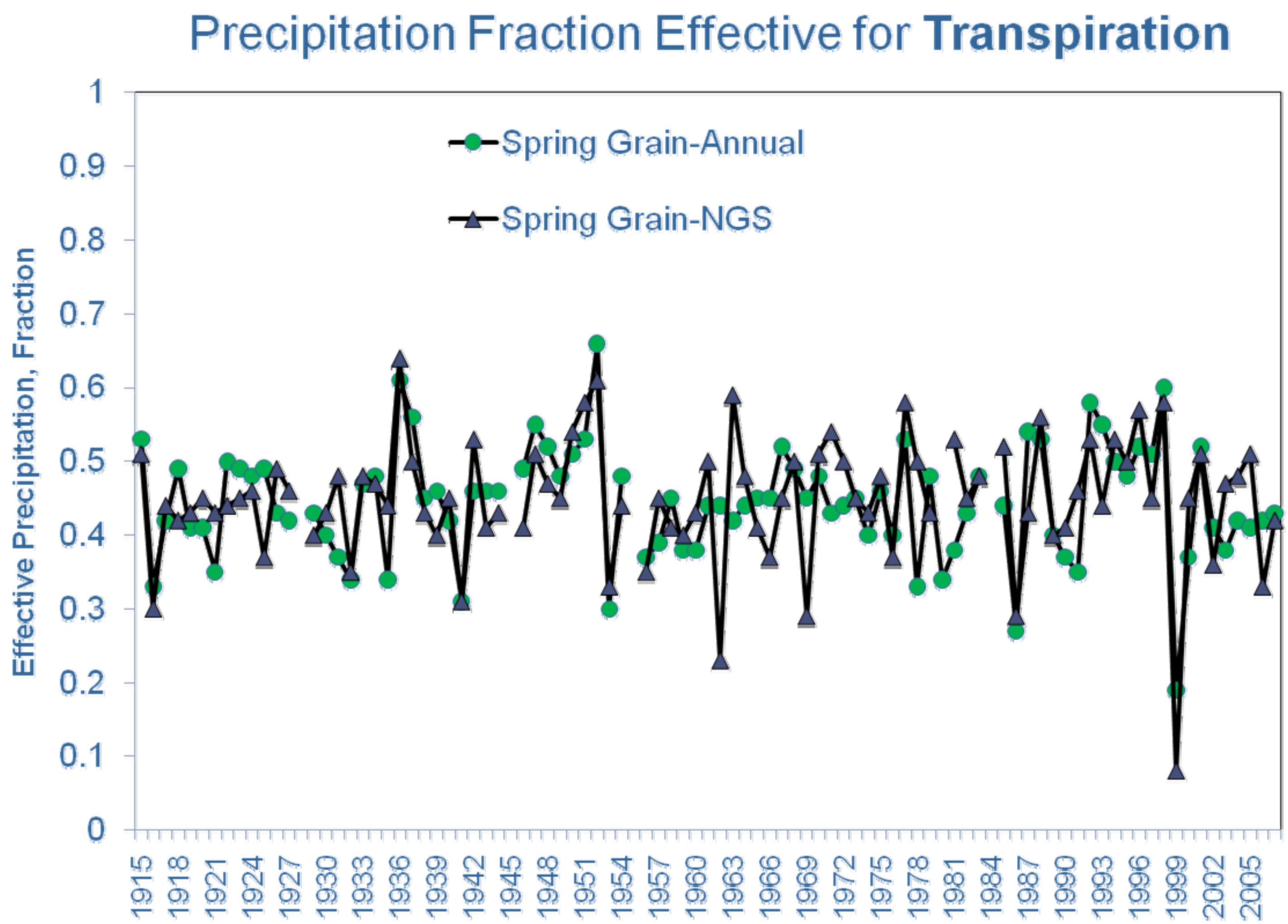
Aberdeen, Idaho --ETIdaho



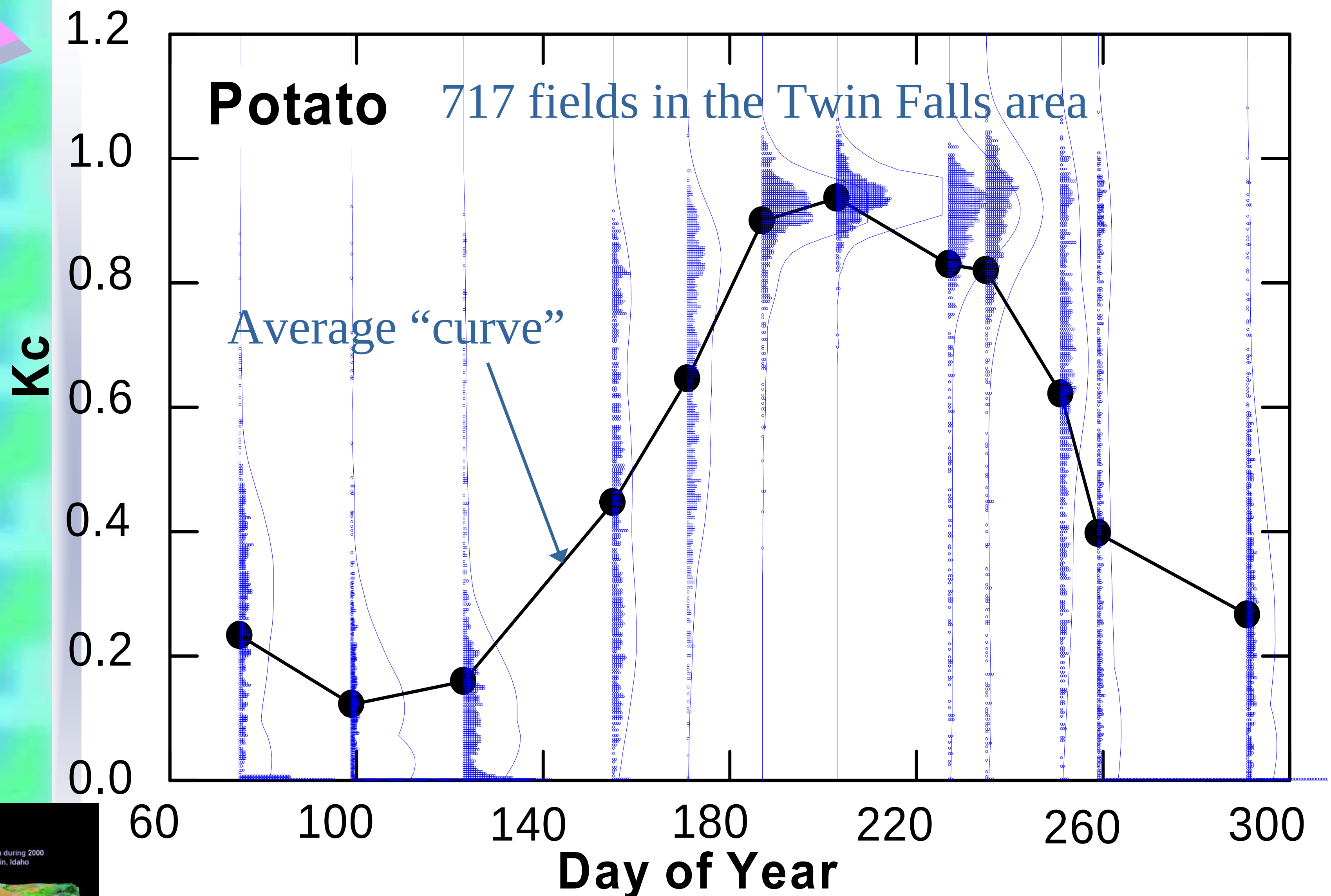
Aberdeen, Idaho --ETIdaho

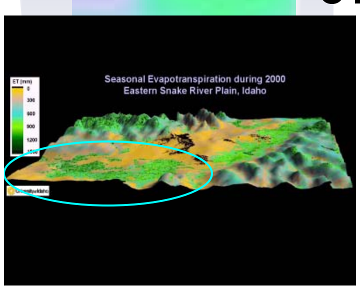


Aberdeen, Idaho --ETIdaho

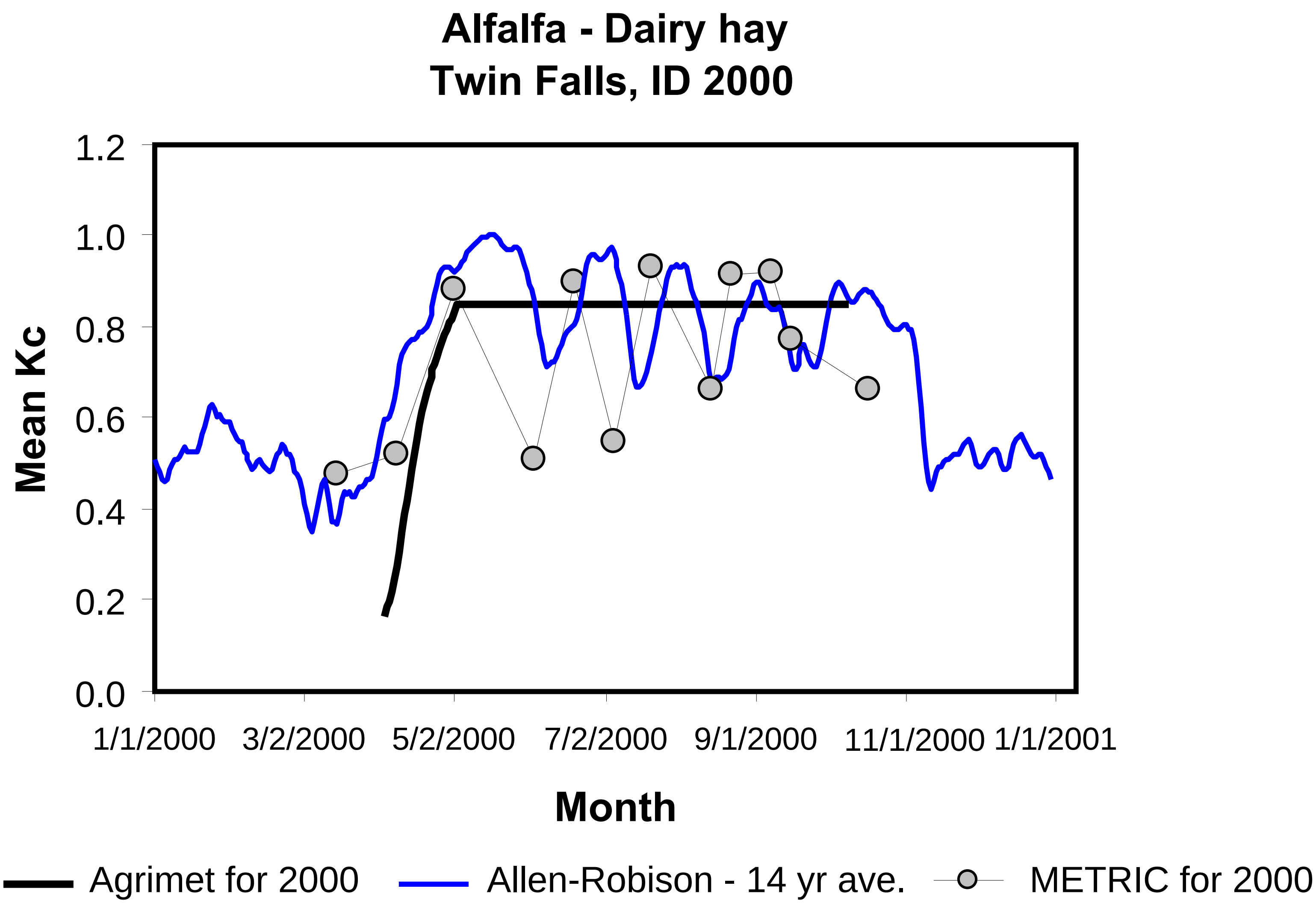


Use to Refine Local Information

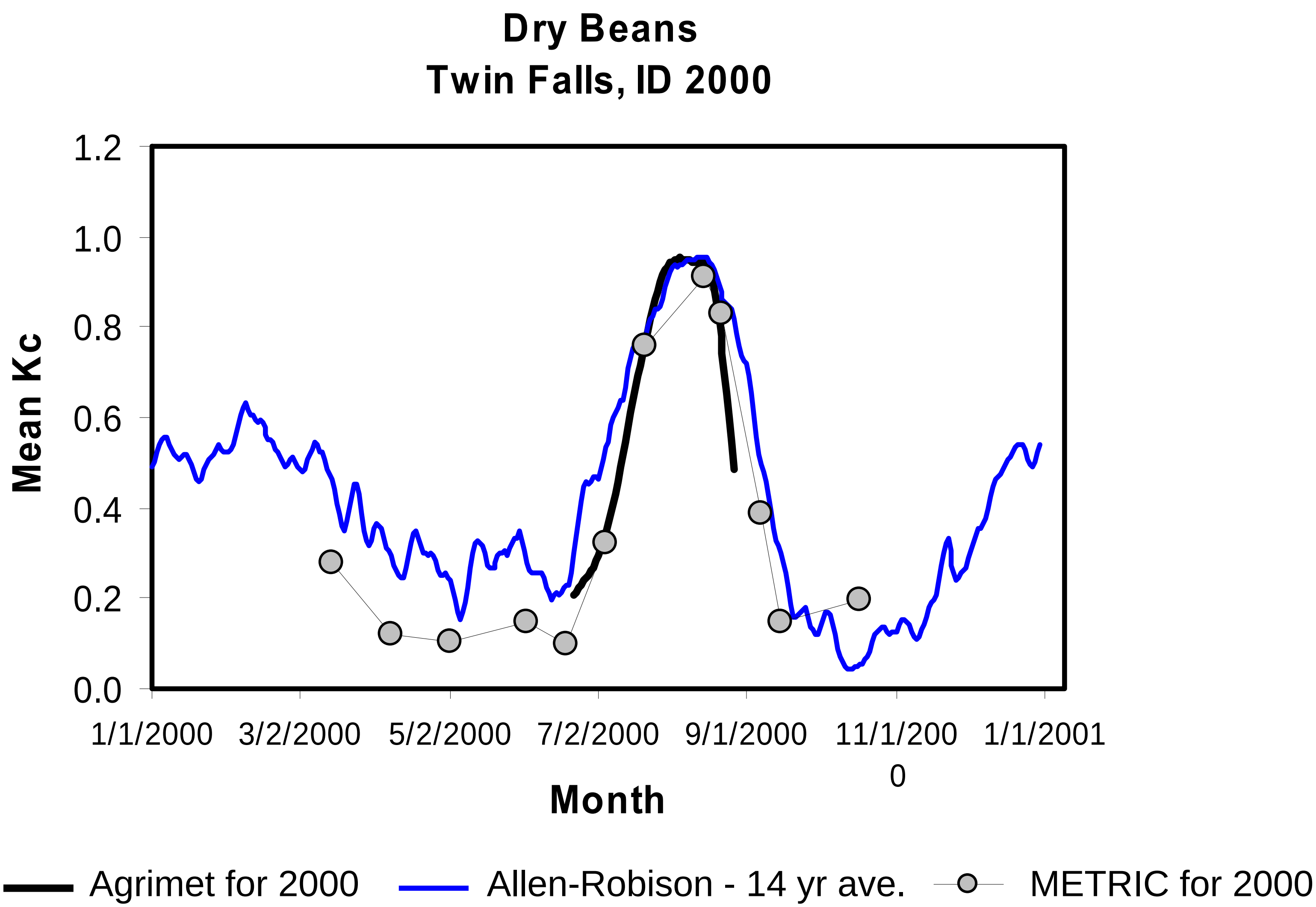


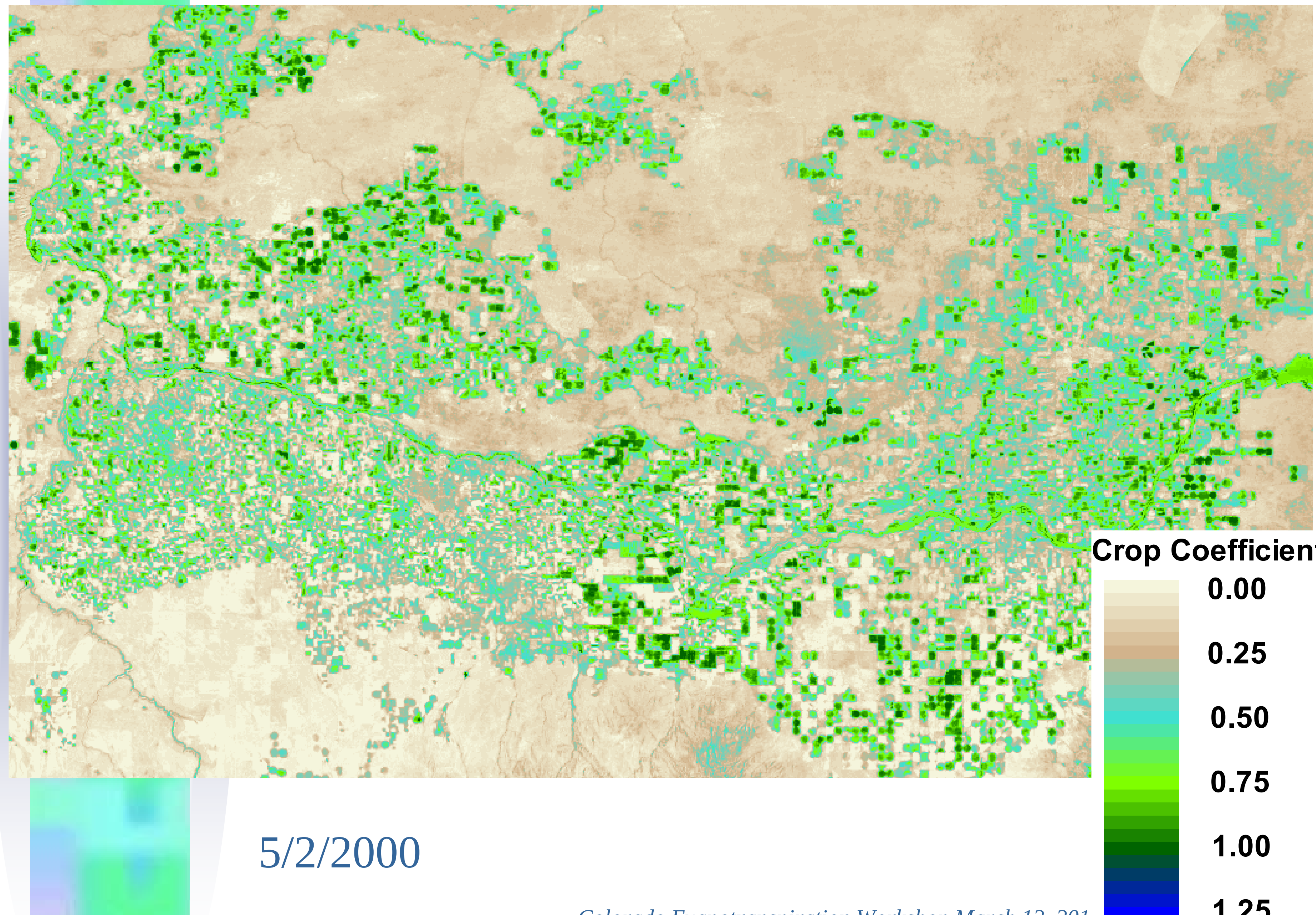


Comparison with K_c from METRIC and K_c based Methods

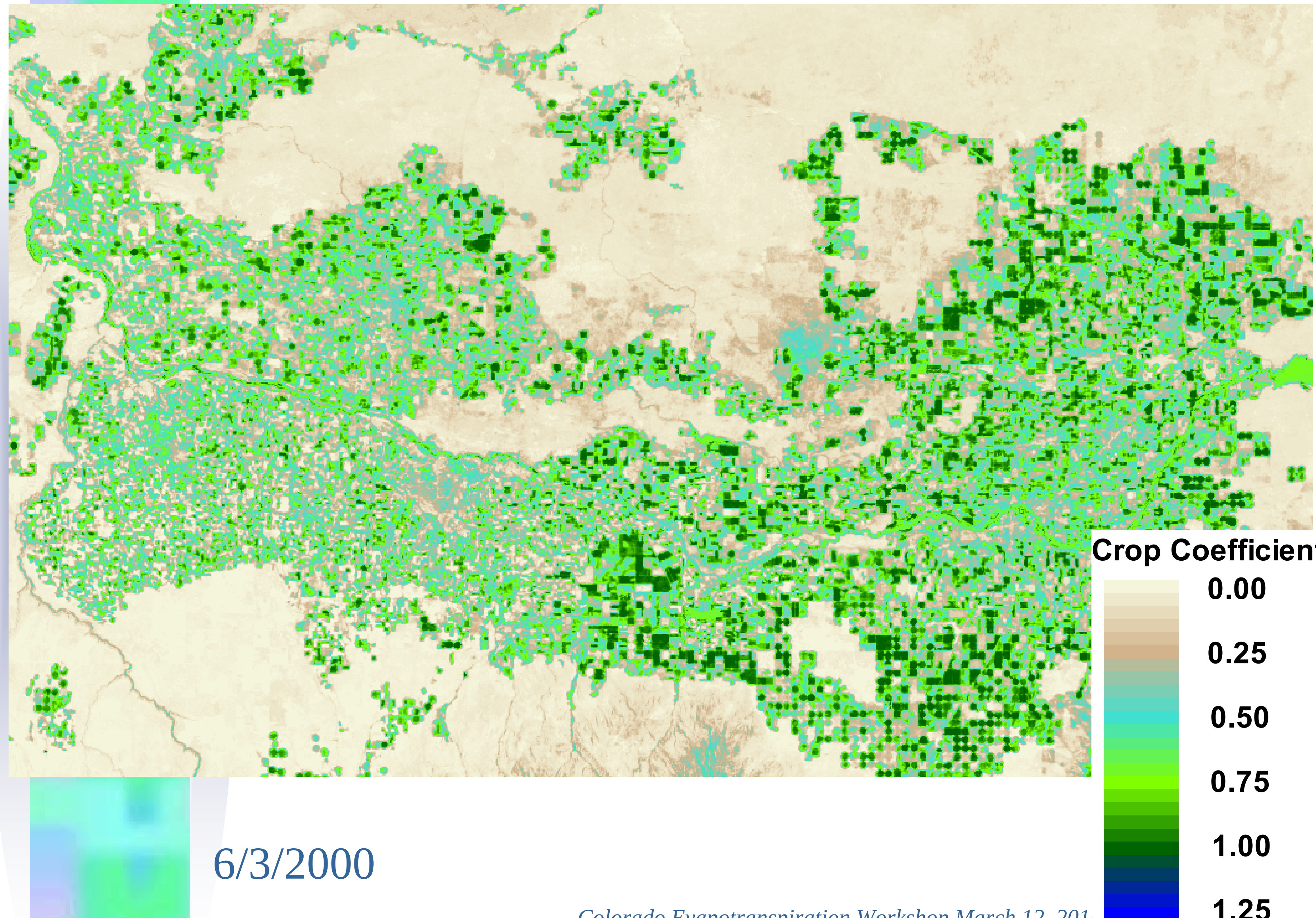


Comparison with K_c from METRIC and K_c based Methods

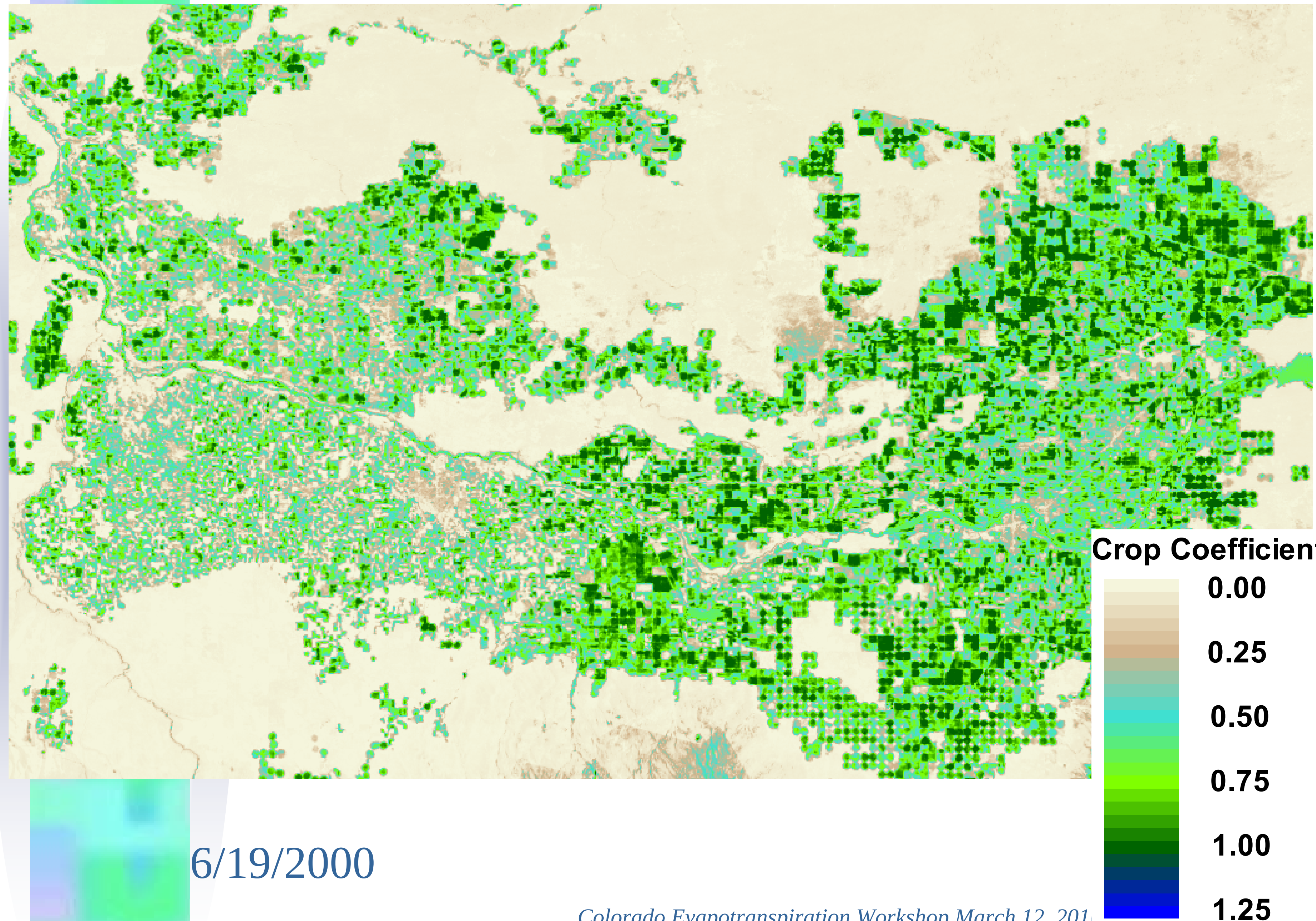




5/2/2000



6/3/2000



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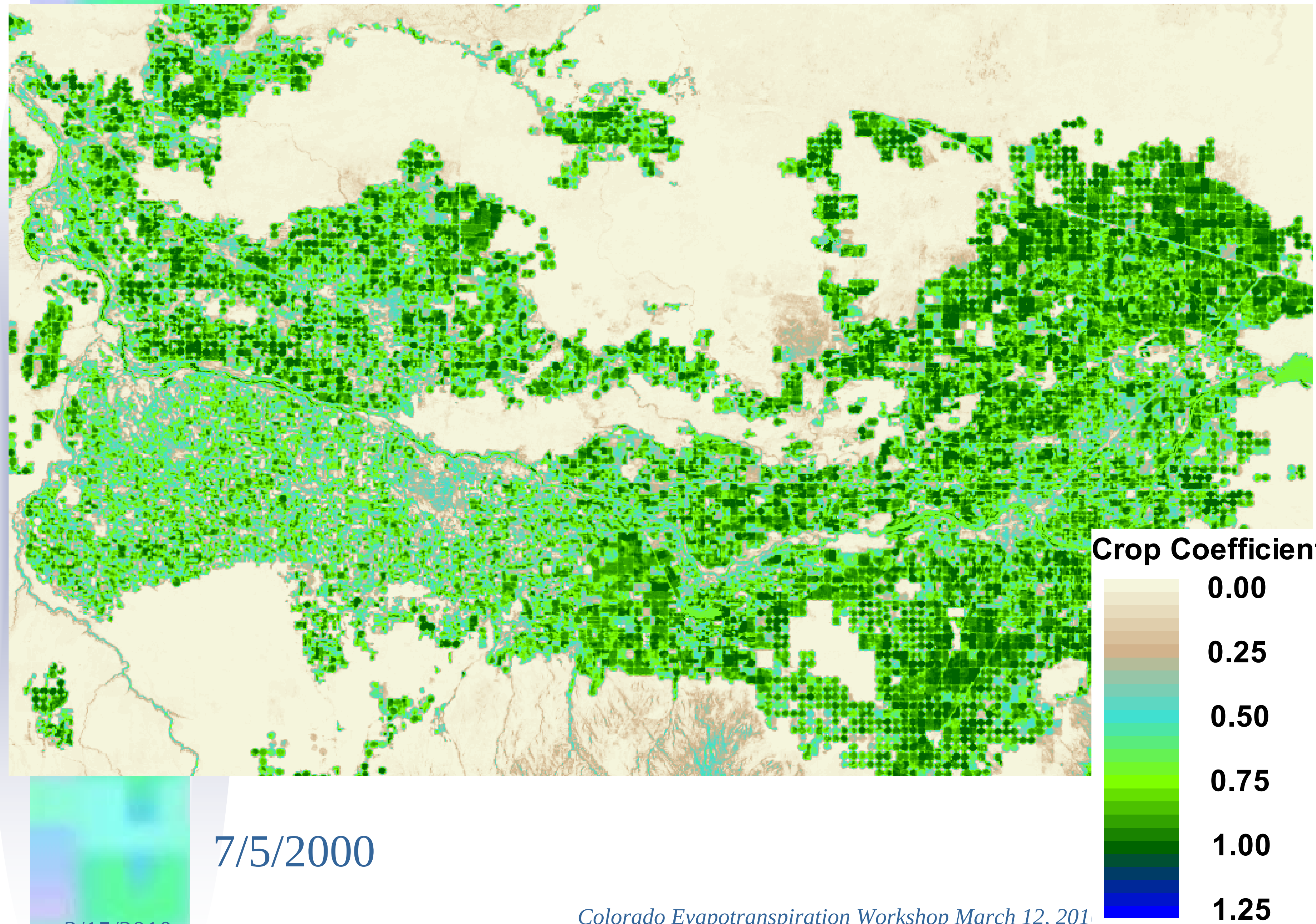
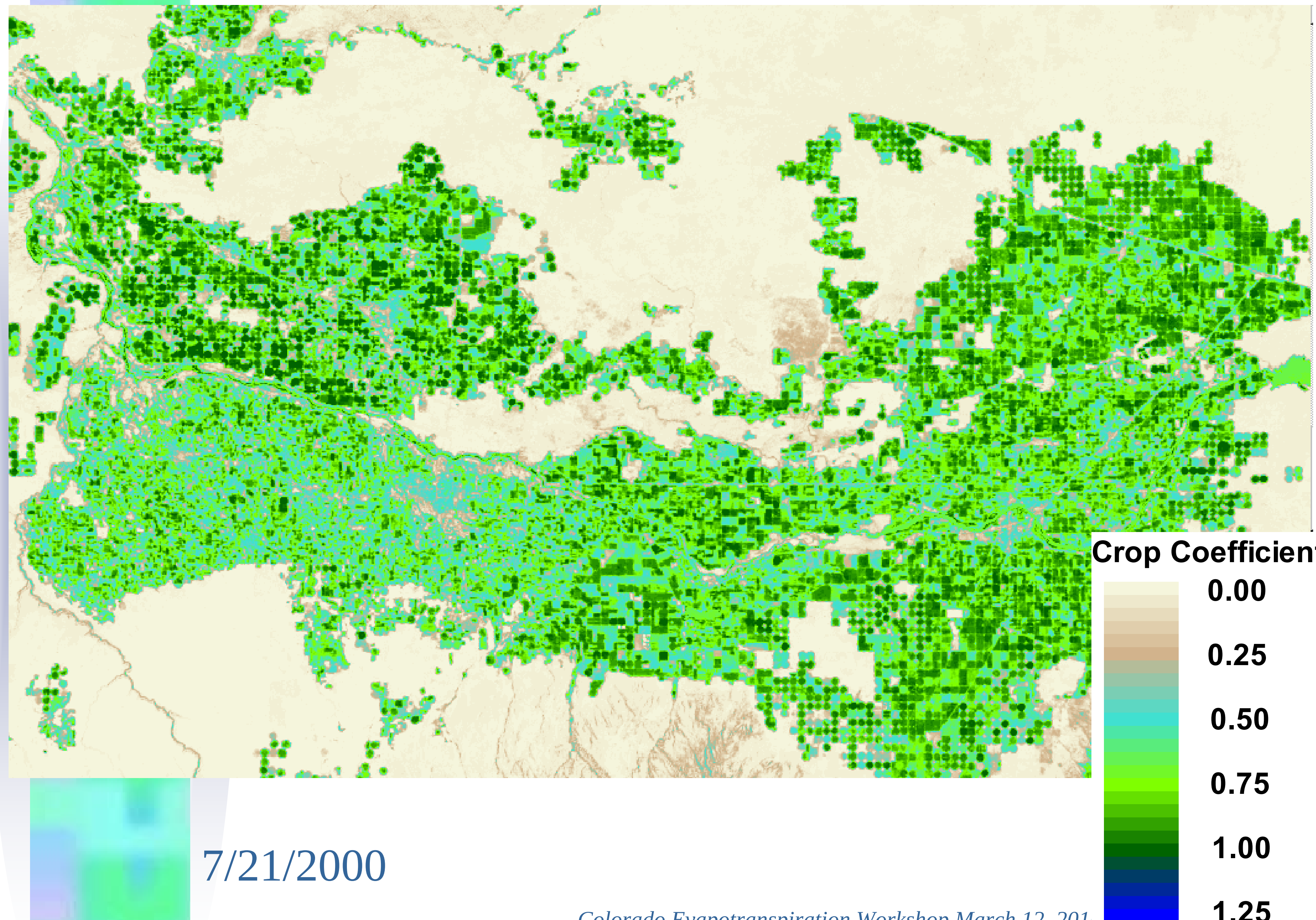
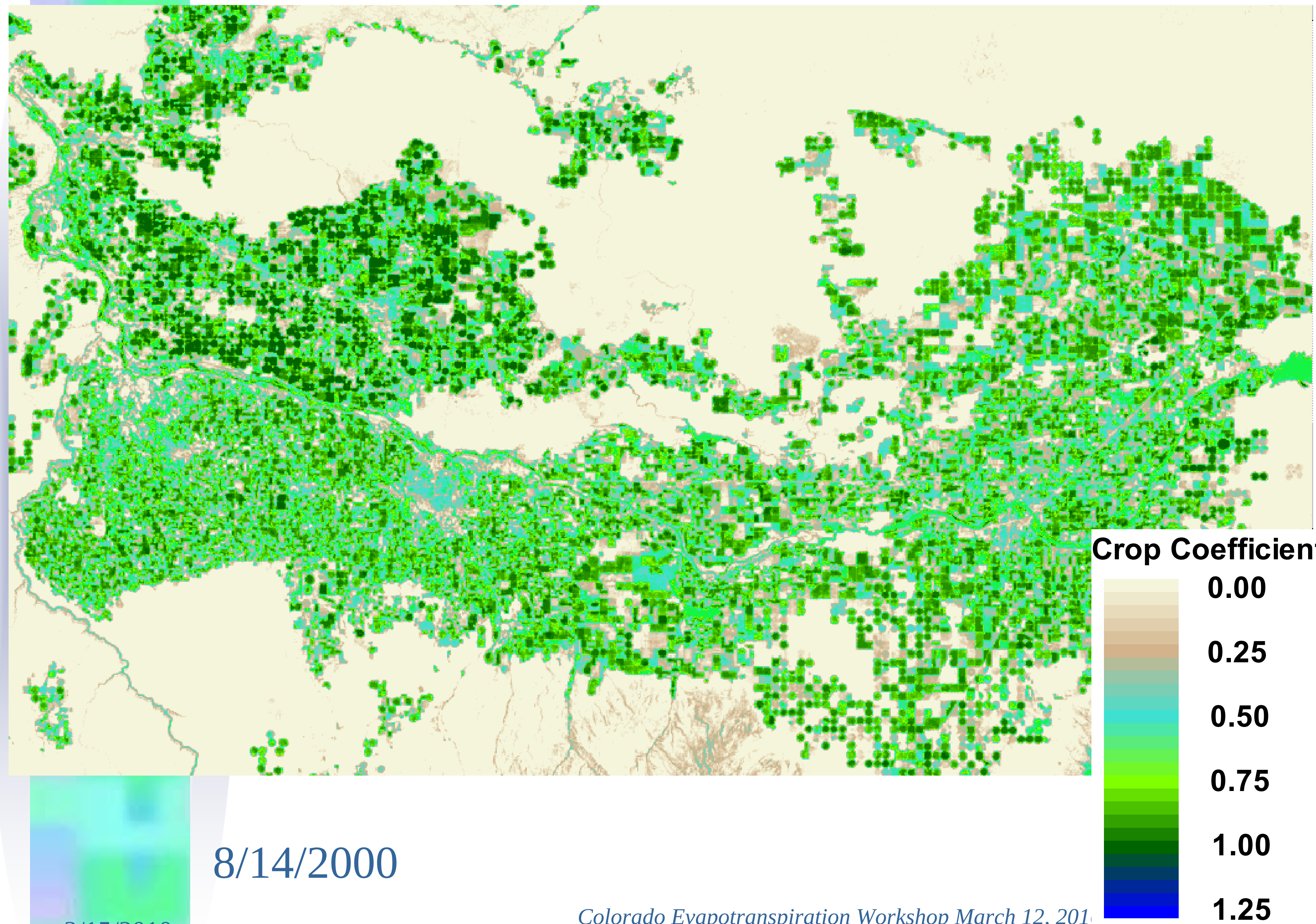


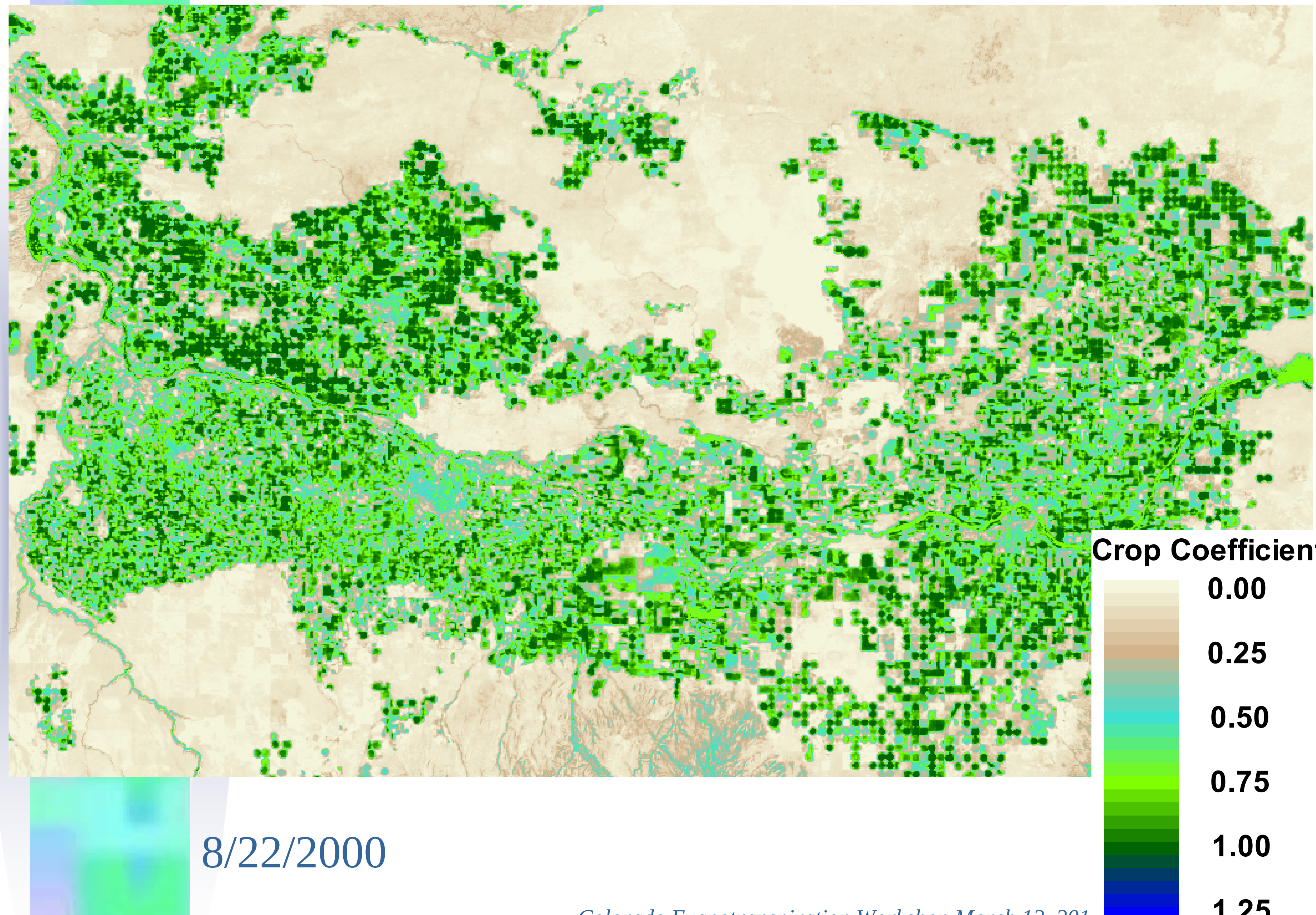
7/5/2000



7/21/2000

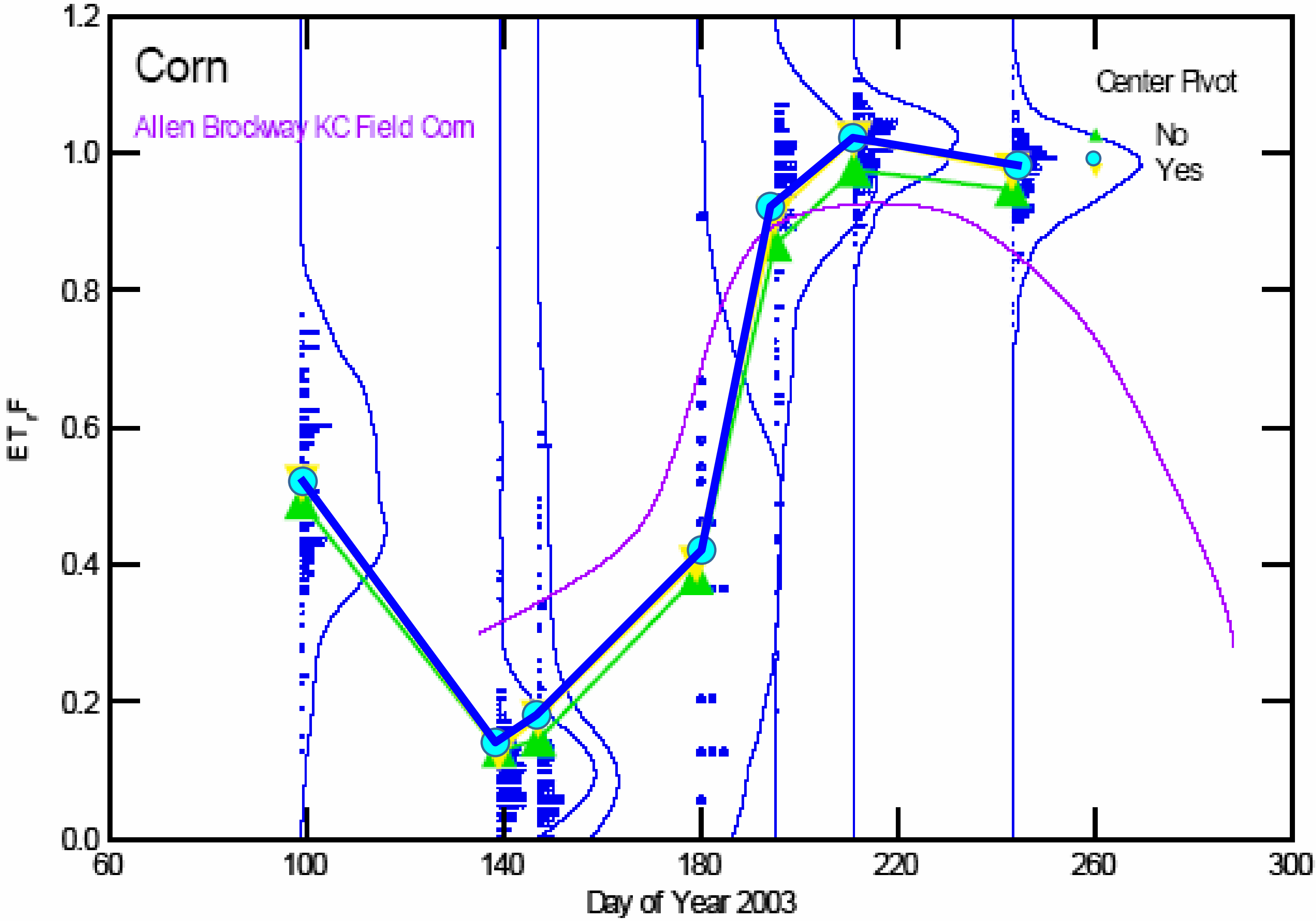


8/14/2000



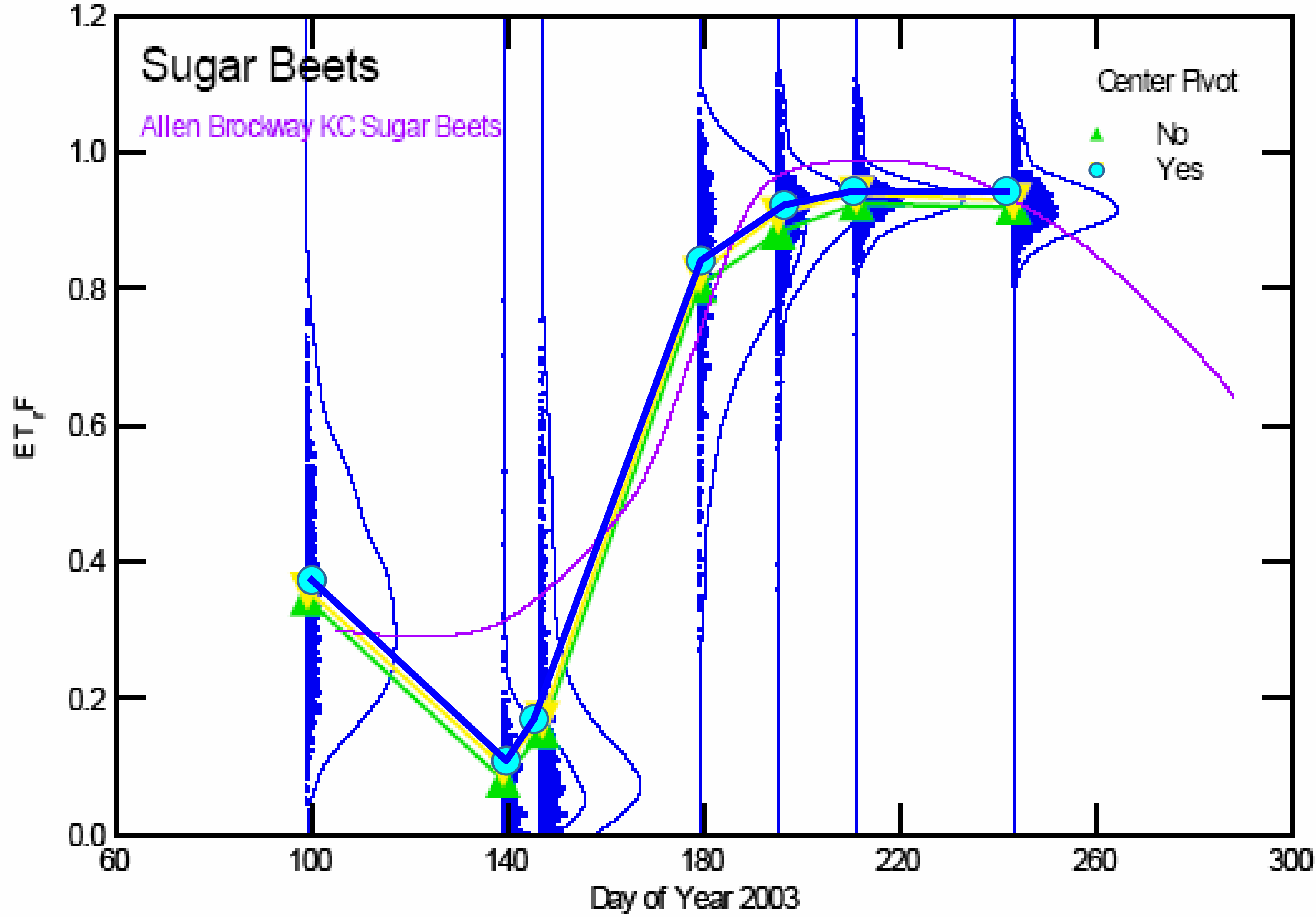
8/22/2000

Impact of Irrigation System Type

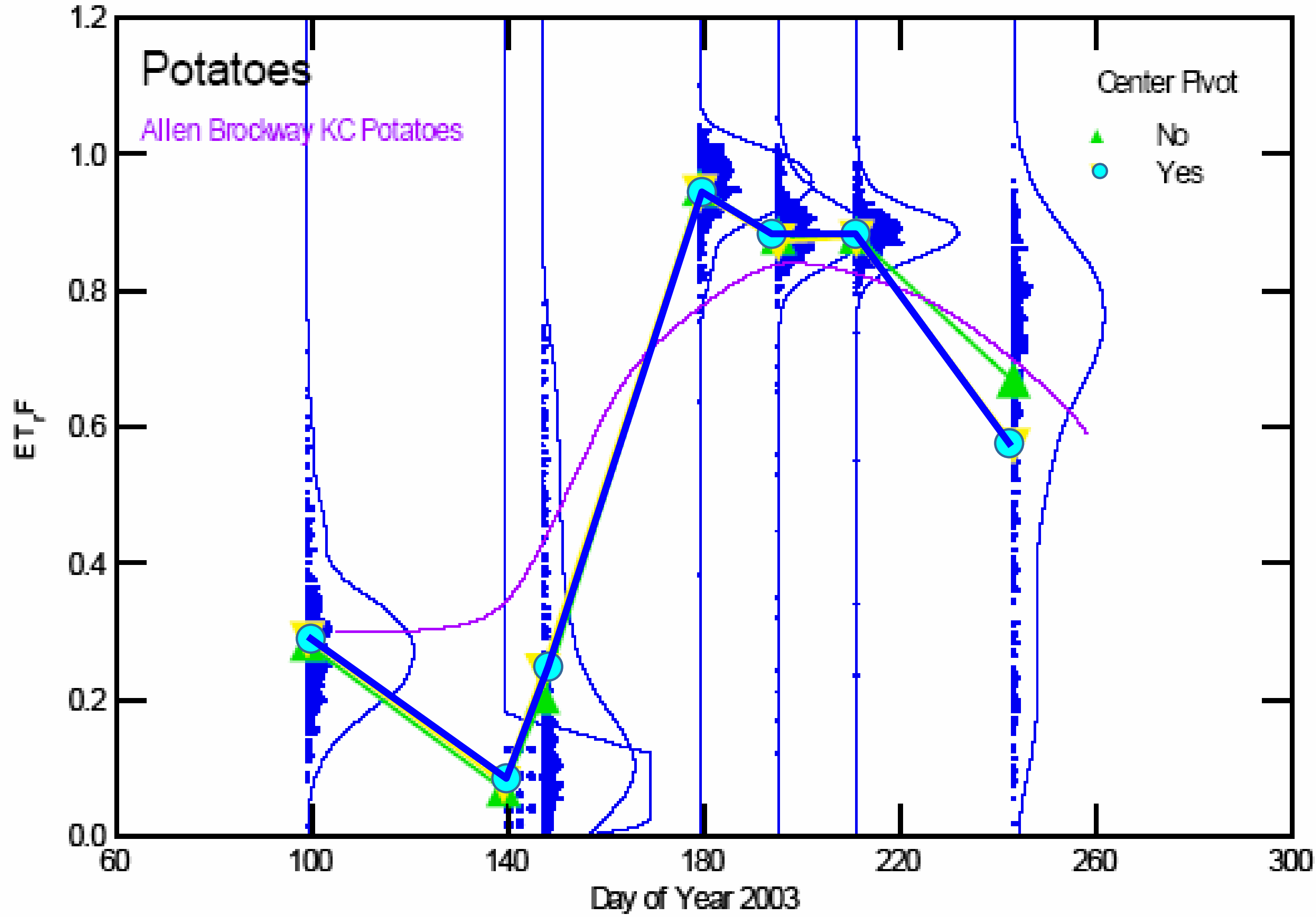


Each "blue dot" is one field.

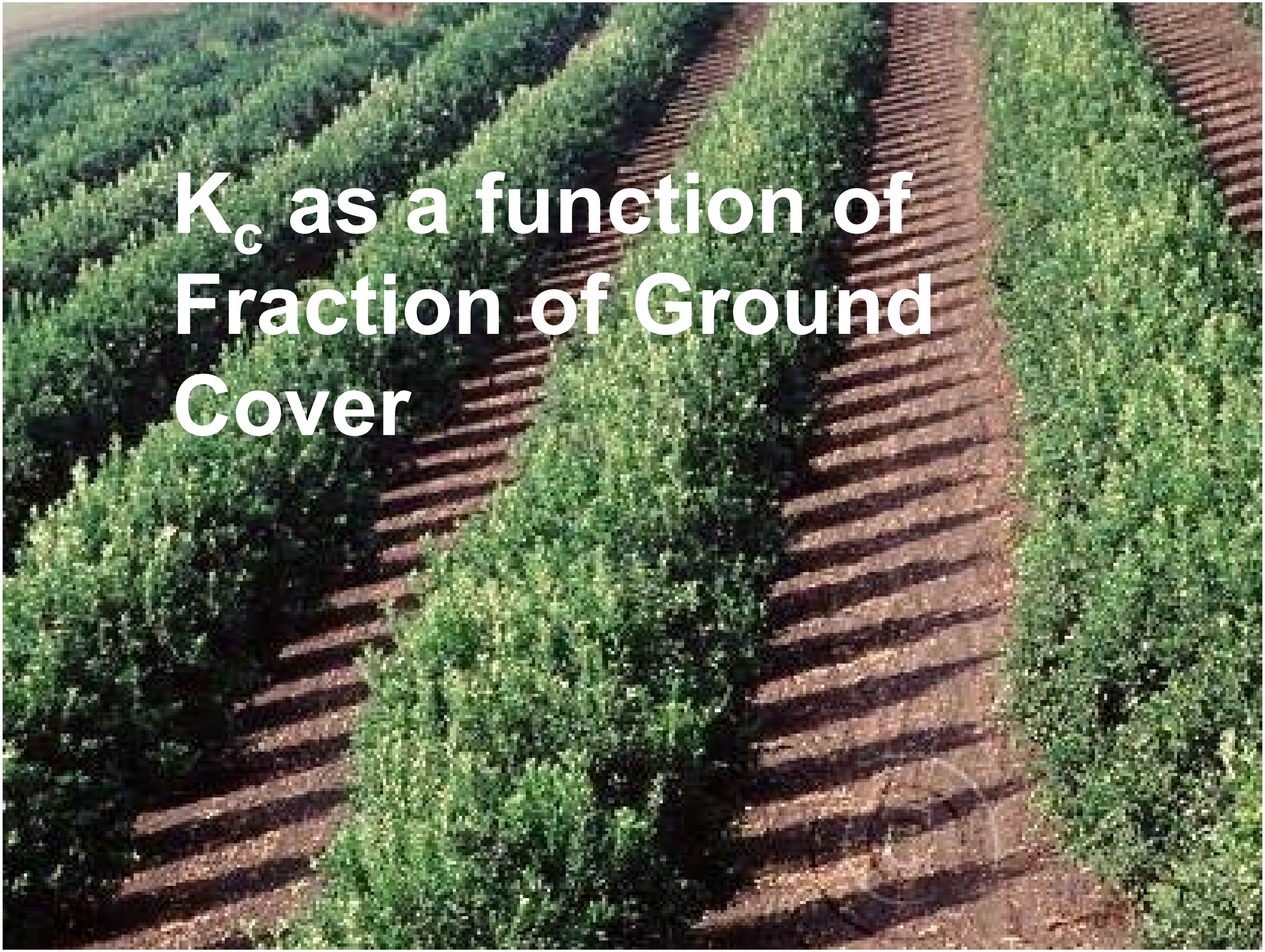
Impact of Irrigation System Type



Impact of Irrigation System Type

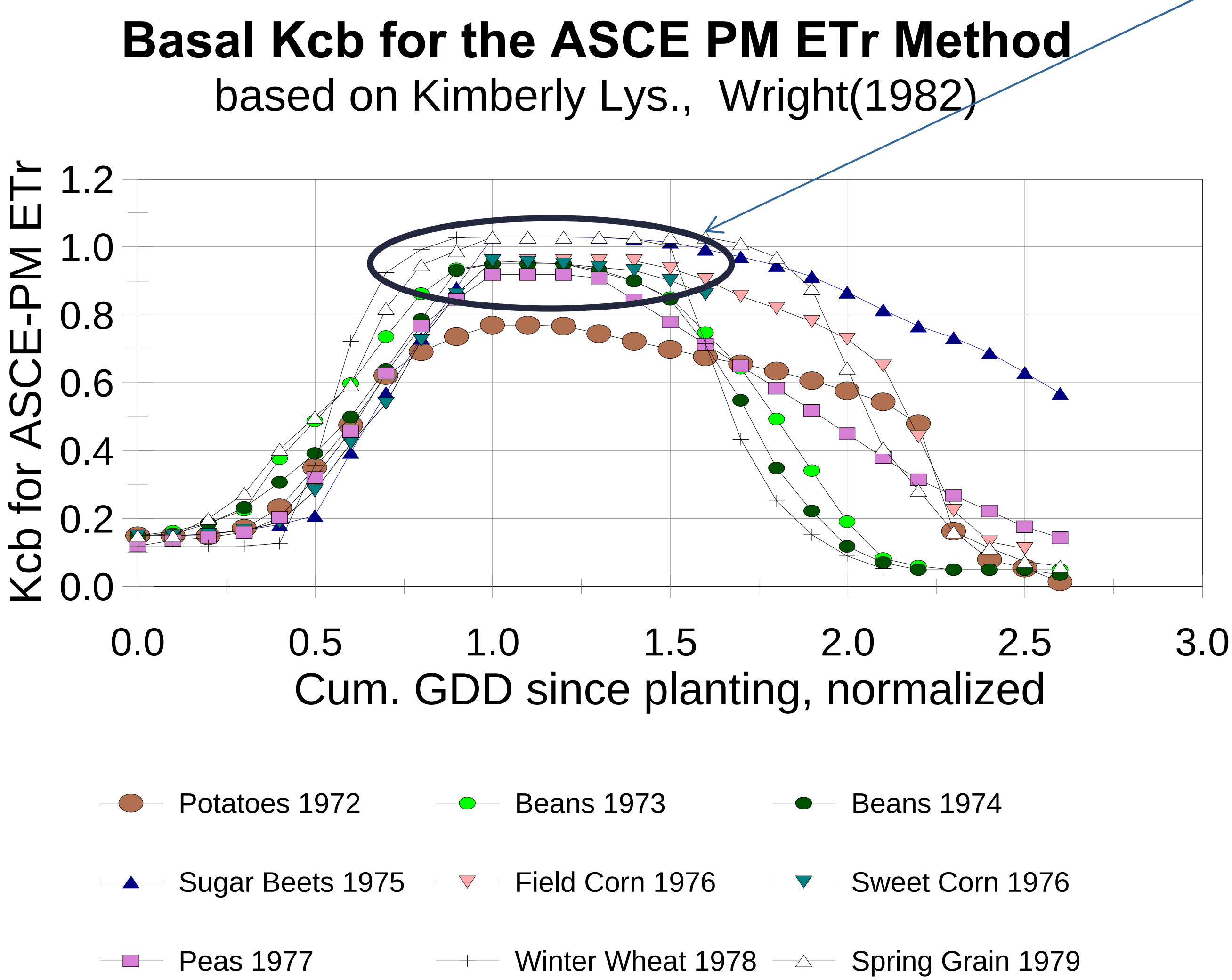


K_c as a function of Fraction of Ground Cover

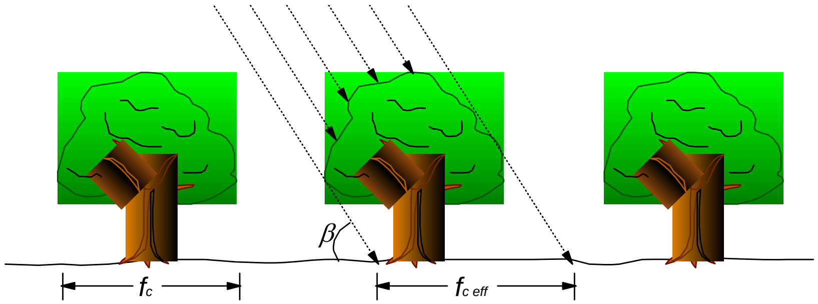


Similarity of $K_{cb\ full}$

Relative Consistency in $K_{cb\ max}$ among many crop types



Question:



- Is it possible to estimate K_c for variable development conditions from:
  - fraction of ground covered by vegetation
    - (to incorporate horizontal solar radiation capture)
  - height of crop
    - (to incorporate effects of:
      - solar radiation intercepted along sides of canopy
      - aerodynamic transfer of energy (roughness effects)

(there are a wide variety of growing conditions for vegetables/trees (row spacing, etc.))

Vegetables

Vineyards

Orchards – bare soil

Orchards – Ground Cover

Even Hops

Color Many Thanks to Roy Lambeth, Edinburgh Scottland for the photo of Hops pickers / stringers. (Hops is used to flavor beer!)

Allen and Pereira 2009, Irrigation Science

--FAO-56 style approach

(assuming bare soil between vegetation)

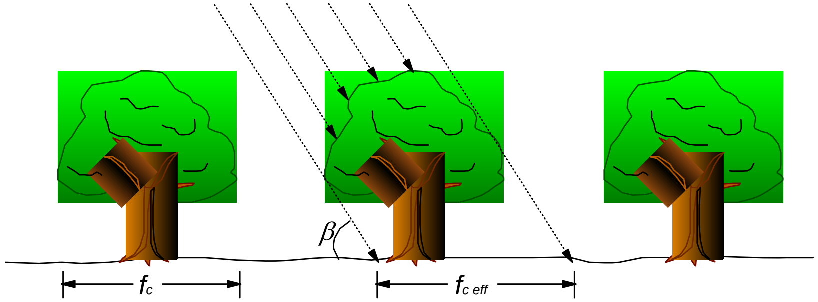
$$K_{cb} = K_{c\min} + K_d \left(K_{cb\ full} - K_{c\min} \right)$$

K_{cmin} = minimum K_{cb} for bare soil (~0.10-0.15)

K_d = density coefficient (0-1)

$K_{cb\ full}$ = K_{cb} for full ground covered by vegetation

Density Coeff.



$$K_d = min\left(1, M_L\, f_{c\,eff}\,, f_{c\,eff}^{\left(\frac{1}{1+h}\right)}\right)$$

K_d = density coefficient (0-1)

M_L = multiplier on $f_{c\ eff}$ (~1.5-2)

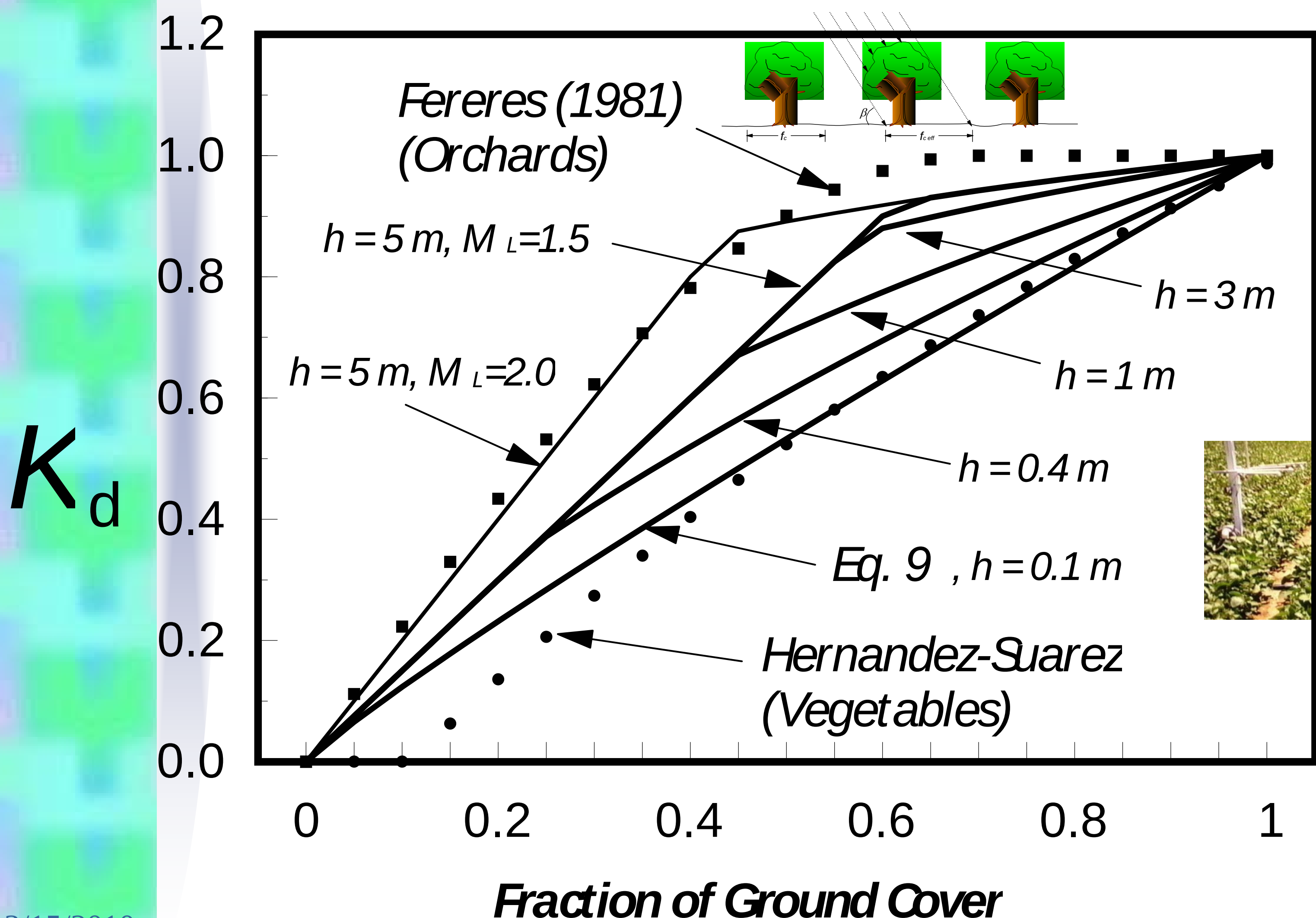
(to set upper flux limit per fraction of cover)

$f_{c\ eff}$ = effective fraction of ground covered (shaded) by vegetation (0-1)

h = height, m *(for radiation + microadvection)*

Density Coeff.

$$K_d = min\left(1, M_L\ f_{c\,eff}\ ,\ f_{c\,eff}^{\left(\frac{1}{1+h}\right)}\right)$$



Expanded K_{co} tables for Orchards

Crop	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$	$K_{cb\ ini}$	K_{cbmid}	$K_{cb\ end}$
Fruit Trees						
Almonds						
- no ground cover - high density (f_{ceff} = 0.7)	**0.40**	**1.00**	**0.70**	**0.20**	**0.95**	**0.65**
- no ground cover - med. density (f_{ceff} = 0.5)	**0.40**	**0.85**	**0.60**	**0.20**	**0.80**	**0.55**
- no ground cover – low dens. / young (f_{ceff} = 0.25)	**0.35**	**0.50**	**0.40**	**0.15**	**0.45**	**0.35**
- active ground cover - high density (f_{ceff} = 0.7)	**0.85**	**1.05**	**0.85**	**0.75**	**1.00**	**0.80**
- active ground cover - med. density (f_{ceff} = 0.5)	**0.85**	**1.00**	**0.85**	**0.75**	**0.95**	**0.80**
- act. grnd cover – low dens. / young (f_{ceff} = 0.25)	**0.85**	**0.95**	**0.85**	**0.75**	**0.90**	**0.80**
Apples, Cherries, Pears						
- no ground cover - high density (f_{ceff} = 0.7)	**0.50**	**1.15**	**0.80**	**0.30**	**1.10**	**0.75**
- no ground cover - med. density (f_{ceff} = 0.5)	**0.50**	**1.05**	**0.75**	**0.30**	**1.004**	**0.70**
- no ground cover - low dens./ young (f_{ceff} = 0.25)	**0.40**	**0.70**	**0.55**	**0.25**	**0.65**	**0.50**
- act. grnd cov., killing frost – h.dens. (f_{ceff} = 0.7)	**0.50**	**1.20**	**0.85**	**0.40**	**1.15**	**0.80**
- act. grnd cov., killing frost – m.dens. (f_{ceff}=0.5)	**0.50**	**1.15**	**0.85**	**0.40**	**1.10**	**0.80**
- act. grnd cov., killing frost – l.dens. (f_{ceff} = 0.25)	**0.50**	**1.05**	**0.85**	**0.40**	**1.00**	**0.80**
- act. grnd cov., no frosts – h. dens. (f_{ceff} = 0.7)	**0.85**	**1.20**	**0.85**	**0.75**	**1.15**	**0.80**
- act. grnd cov., no frosts – m. dens. (f_{ceff} = 0.5)3	**0.85**	**1.15**	**0.85**	**0.75**	**1.10**	**0.80**
- act. grnd cov., no frosts – l. dens. (f_{ceff} = 0.25)	**0.85**	**1.05**	**0.85**	**0.75**	**1.00**	**0.80**

for Orchards with ground cover

$$K_{cb} = K_{cb\ cover} + K_d \left(\max \left[K_{cb\ full} - K_{cb\ cover}, \frac{K_{cb\ full} - K_{cb\ cover}}{2} \right] \right)$$

- $K_{cb\ cover}$ = K_{cb} for ground cover (understory)
- K_d = density coefficient (0-1)
- $K_{cb\ full}$ = K_{cb} for full ground covered by vegetation

Note: $K_{cb\ cover}$ may be > $K_{cb\ full}$ due to less stomatal regulation by ground cover

$K_{cb\ full}$ (to represent 100% ground cover)

for grass ET_o *(following FAO-56)*

$$K_{cb\ full} = F_r \left(\min\left(1.0 + 0.1h,\ 1.20\right) + \left[0.04(u_2 - 2) - 0.004(\mathrm{RH}_{\min} - 45)\right]\left(\frac{h}{3}\right)^{0.3} \right)$$

for alfalfa ET_r:

$$K_{cb\ full} = F_r \left(\min\left(0.8 + 0.1h,\ 1.0\right)\right)$$

h = canopy height, m, (limited to 2 m)

F_r = <u>reducer for stomatal resistance</u> > standard annual crops (0-1)

u_2, RH_{min} = wind speed, m/s, min. RH, %

Reducer for stomatal resistance > 100 s m^{-1}

from FAO-56:

$$F_r \approx \frac{\Delta + \gamma(1 + 0.34u_2)}{\Delta + \gamma\left(1 + 0.34u_2 \frac{r_l}{100}\right)}$$

r_l = single leaf stomatal resistance, s m^{-1}

u_2 = wind speed, m/s

(some trees exercise substantial stomatal control)

(F_r represents a full cover LAI of about 3 to 5)

Allen and Pereira 2009, Irrigation Science

to calculate a 'mean' K_c (single)

$$K_{cm} = K_{soil} + K_d \left(\max\left[K_{c\,full} - K_{soil}, \frac{K_{c\,full} - K_{soil}}{2} \right] \right)$$

K_{soil} = averaged K_e for soil

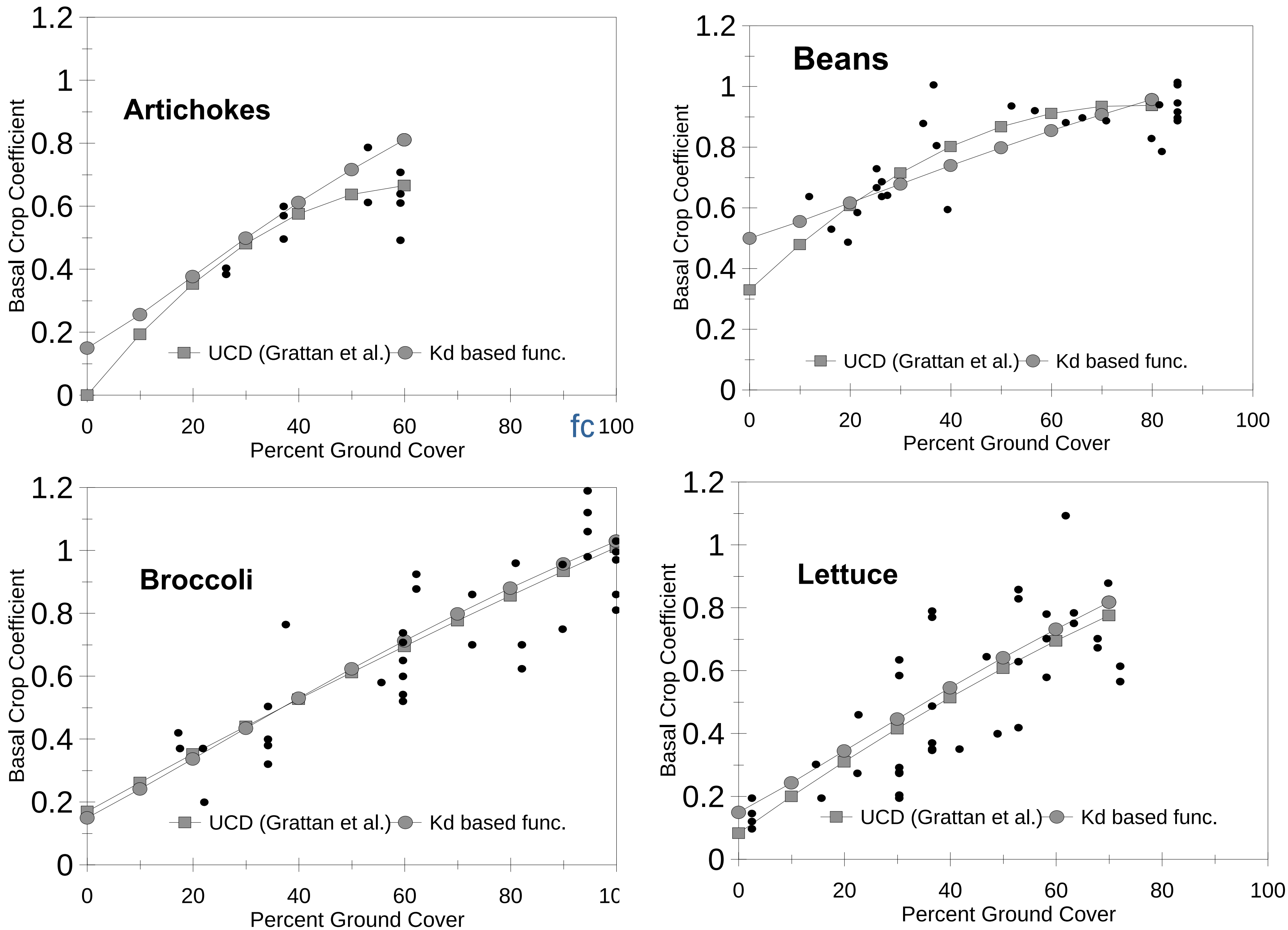
K_d = density coefficient (0-1)

$K_{c\,full}$ = K_c for full ground covered by vegetation (with some background evaporation)

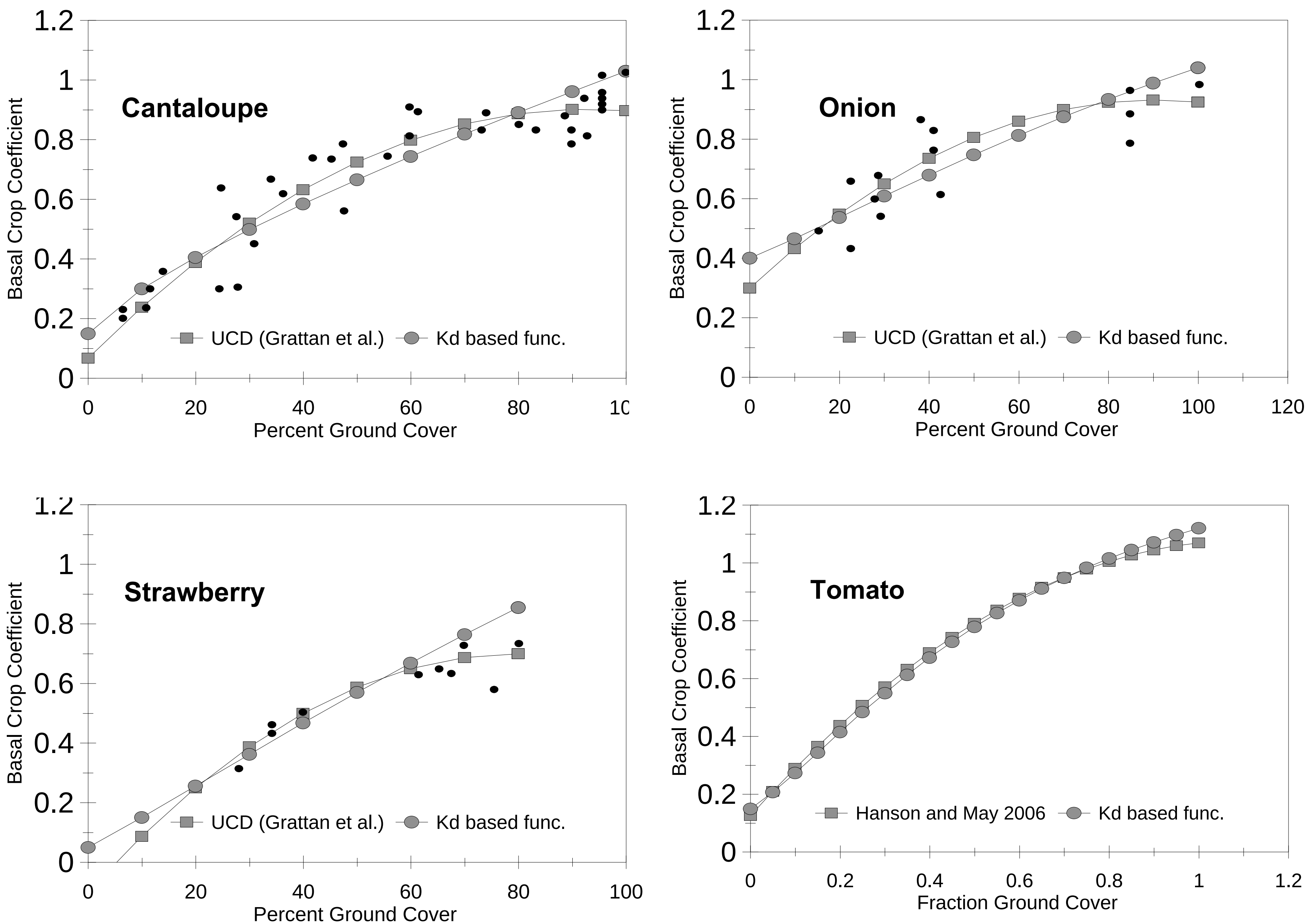
Comparison against Grattan et al. 1998 for development period of vegetables

Crop	Artichoke	Beans	Brocolli	Lettuce	Cantaloupe/ Honeydew	Onion	Strawberry	Tomato
K_{soil}	0.15	0.50	0.15	0.15	0.15	0.40	0.05	0.15
M_L	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
F_r	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Max h, m	0.6	0.4	0.3	0.3	0.3	0.4	0.2	1.2
h vs. t	in prop. to f_c	in prop. to f_c	in prop. to f_c	in prop. to f_c	constant	in prop. to f_c	in prop. to f_c	in prop. to f_c
u_2, ms^{-1}	2	2	2	2	2	2	2	2
RH_{min}, %	45	45	45	45	45	45	45	45

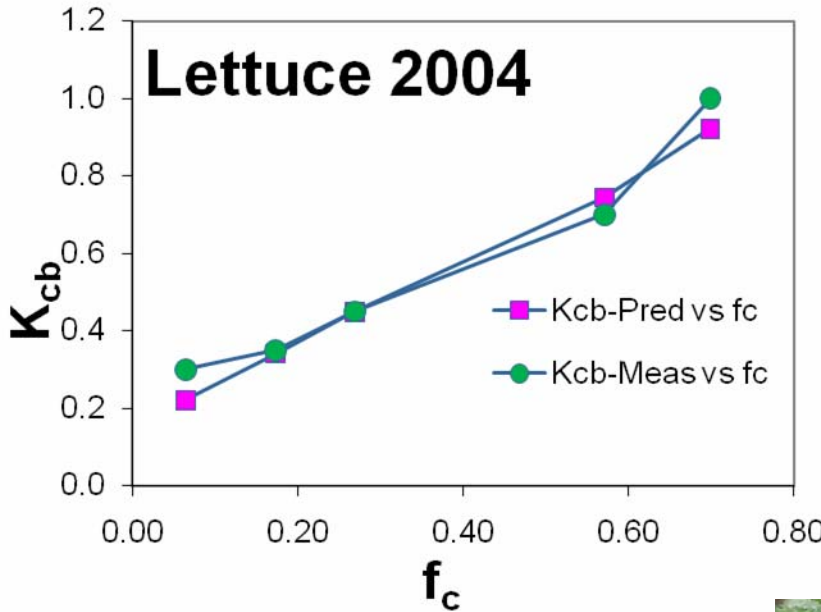
Grattan et al. 1998 *(based on Bowen Ratio)*

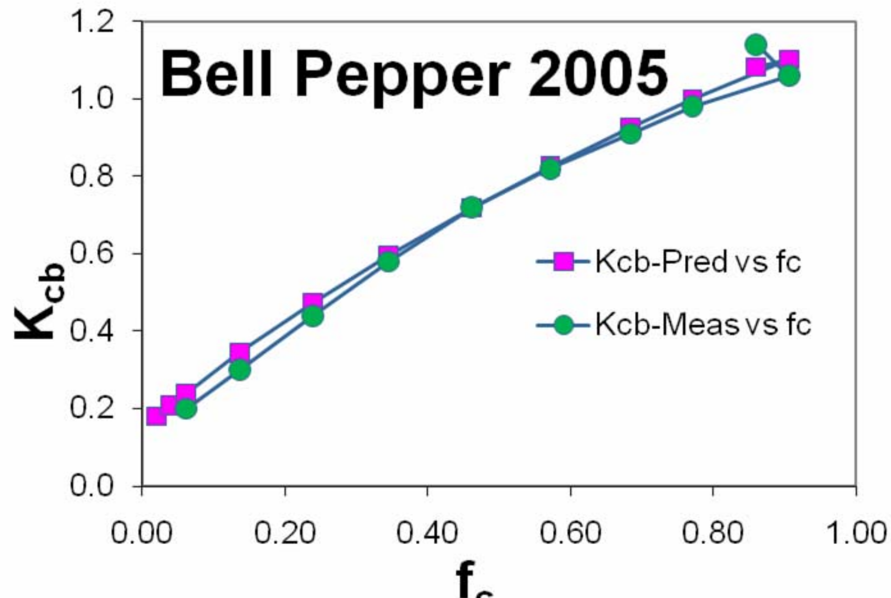


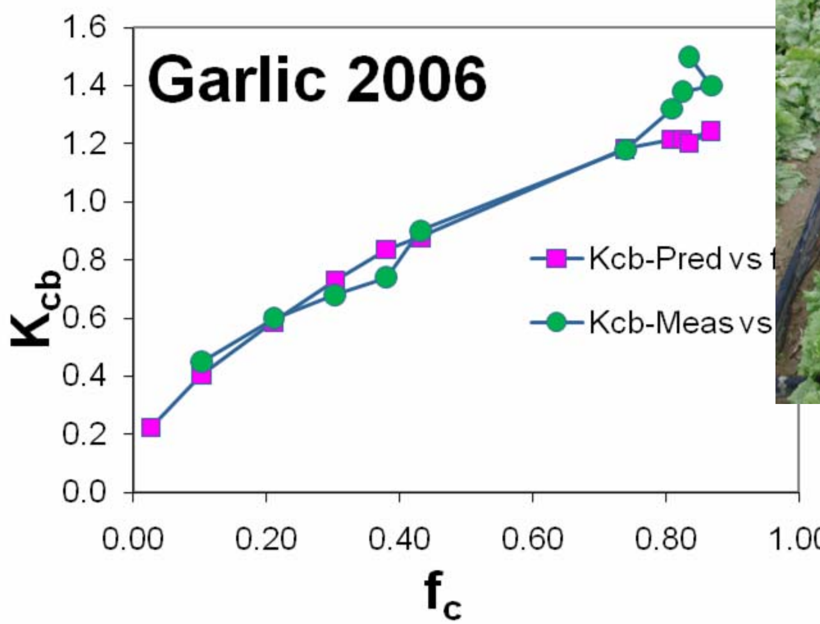
Grattan et al. 1998 (and Hanson and May, 2006)



Fresno, CA Lysimeter Data from Dr. Thomas Trout, USDA-ARS, Fort Collins







Comparison against Grattan et al. 1998 for development period of vegetables

Crop	Artichoke	Beans	Brocolli	Lettuce	Cantaloupe/ Honeydew	Onion	Strawberry	Tomato
no. obs.	11	27	34	39	35	14	10	--
$RMSE_{Grattan}$	0.09	0.09	0.13	0.16	0.09	0.10	0.05	--
$RMSE_{Est.}$	0.15	0.10	0.14	0.17	0.10	0.11	0.10	--


13
ET

Transferability of K_c's

Across locations and climates

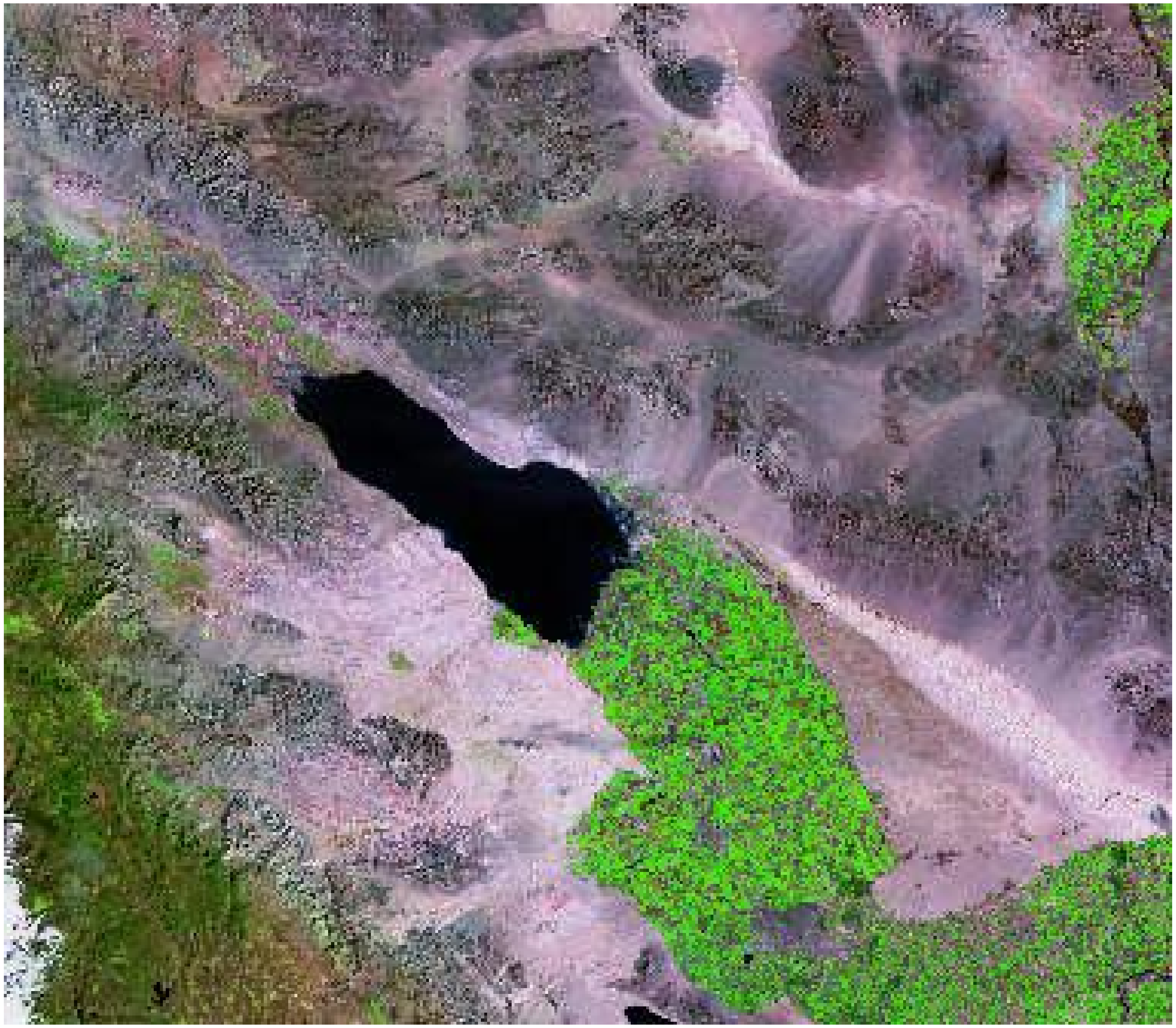
Basic truths:

• Reference ET represents evaporative power of the environment (location)

•K_c represents a scaling of ET_r according to crop type, density, size, ground-cover

Therefore, K_c (and ET_r method) should transfer well.

Example: Imperial Valley, CA



Allen et al., 2005, ASCE J. IDE

Water Balance

ET = Inflow - Surface Outflow

+ Precipitation

- Δ Soil Water

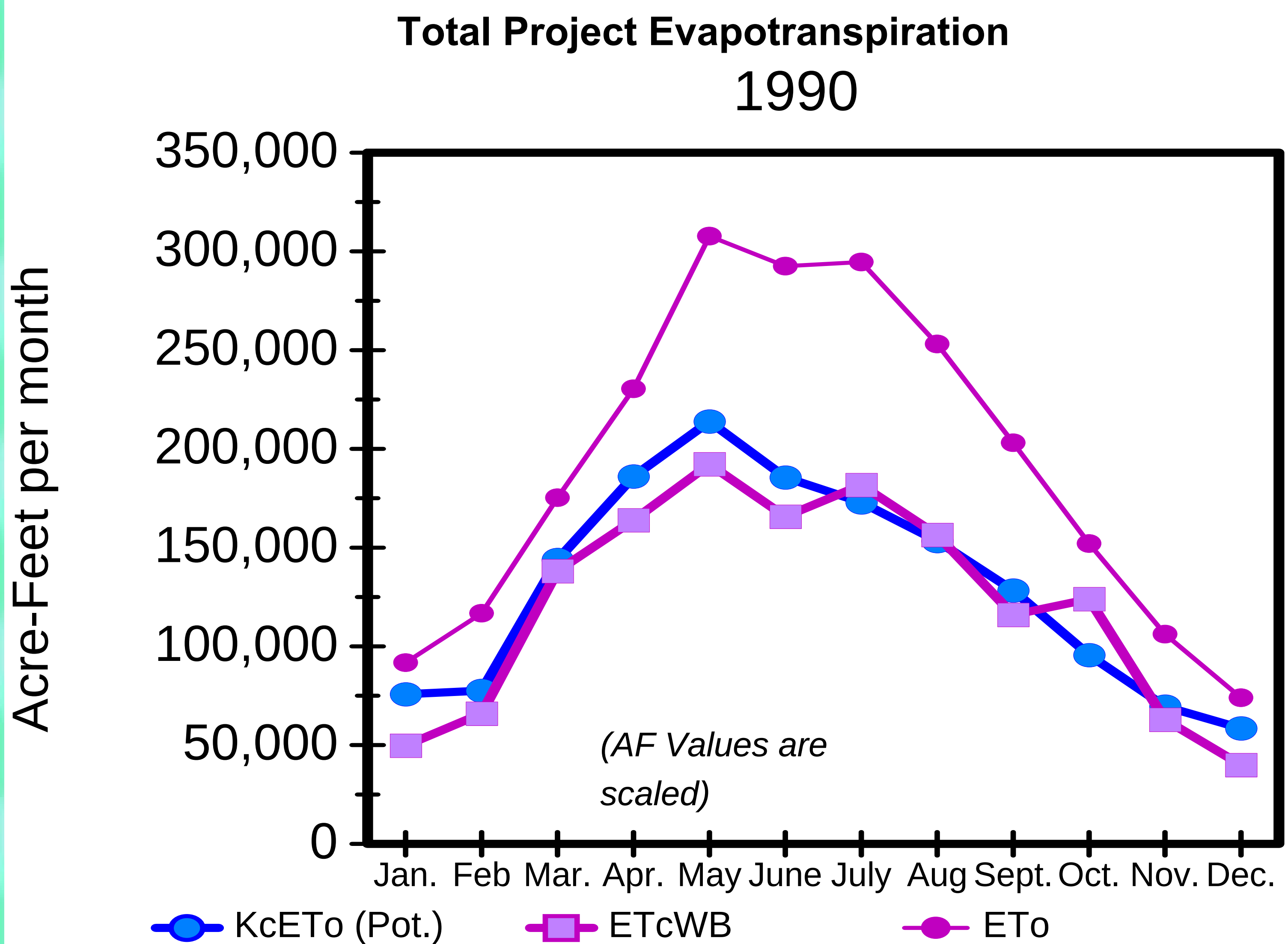
- Deep Percolation

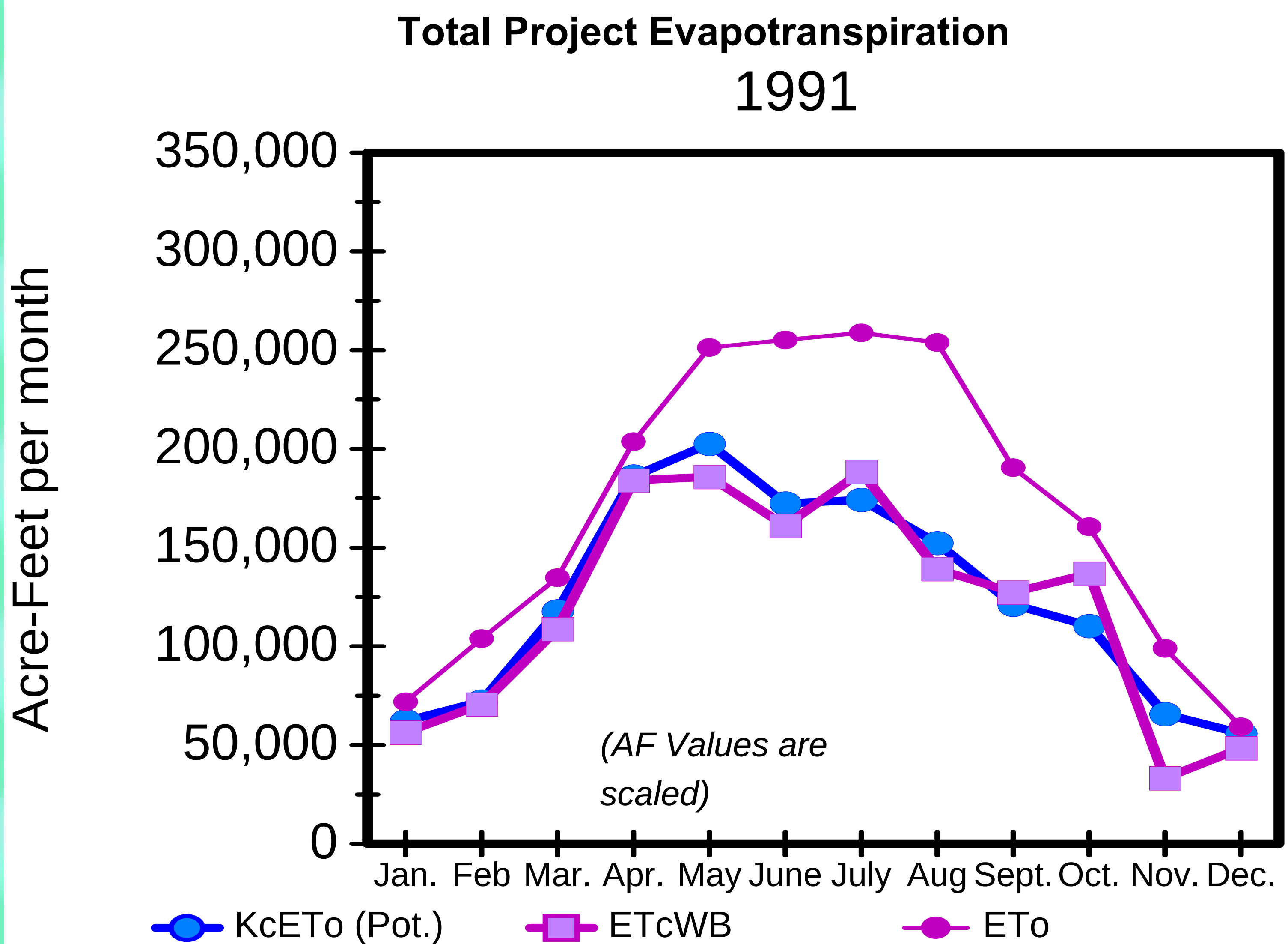
More than 40 types of crops modeled

Acreage of each crop changed each year

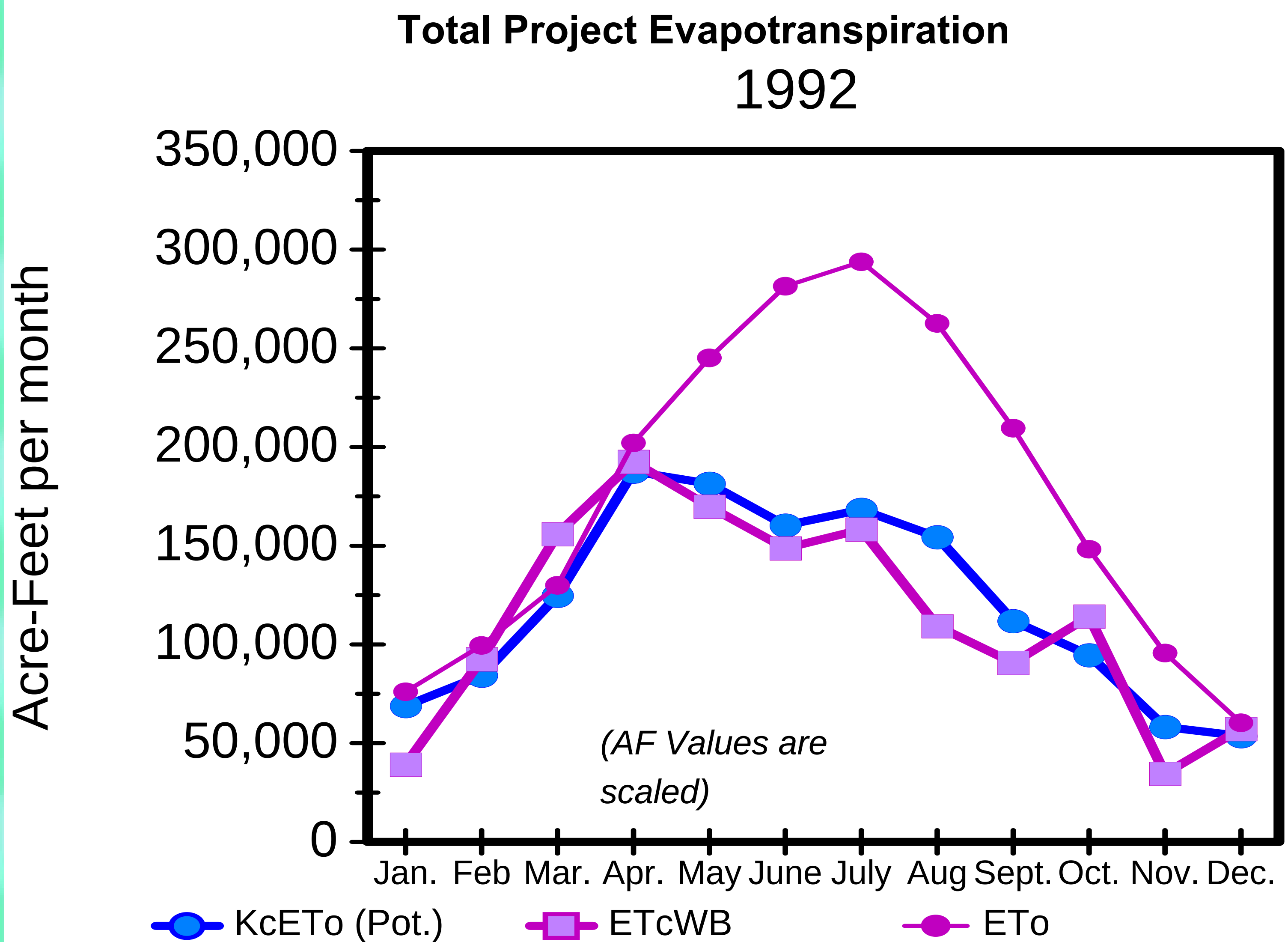
- **accuracy of annual ET from the water balance is +/- 5% (95% C.I.)**

K_c's from Central Valley-based literature were used with FAO-56 grass reference ET_o. Dual method was used

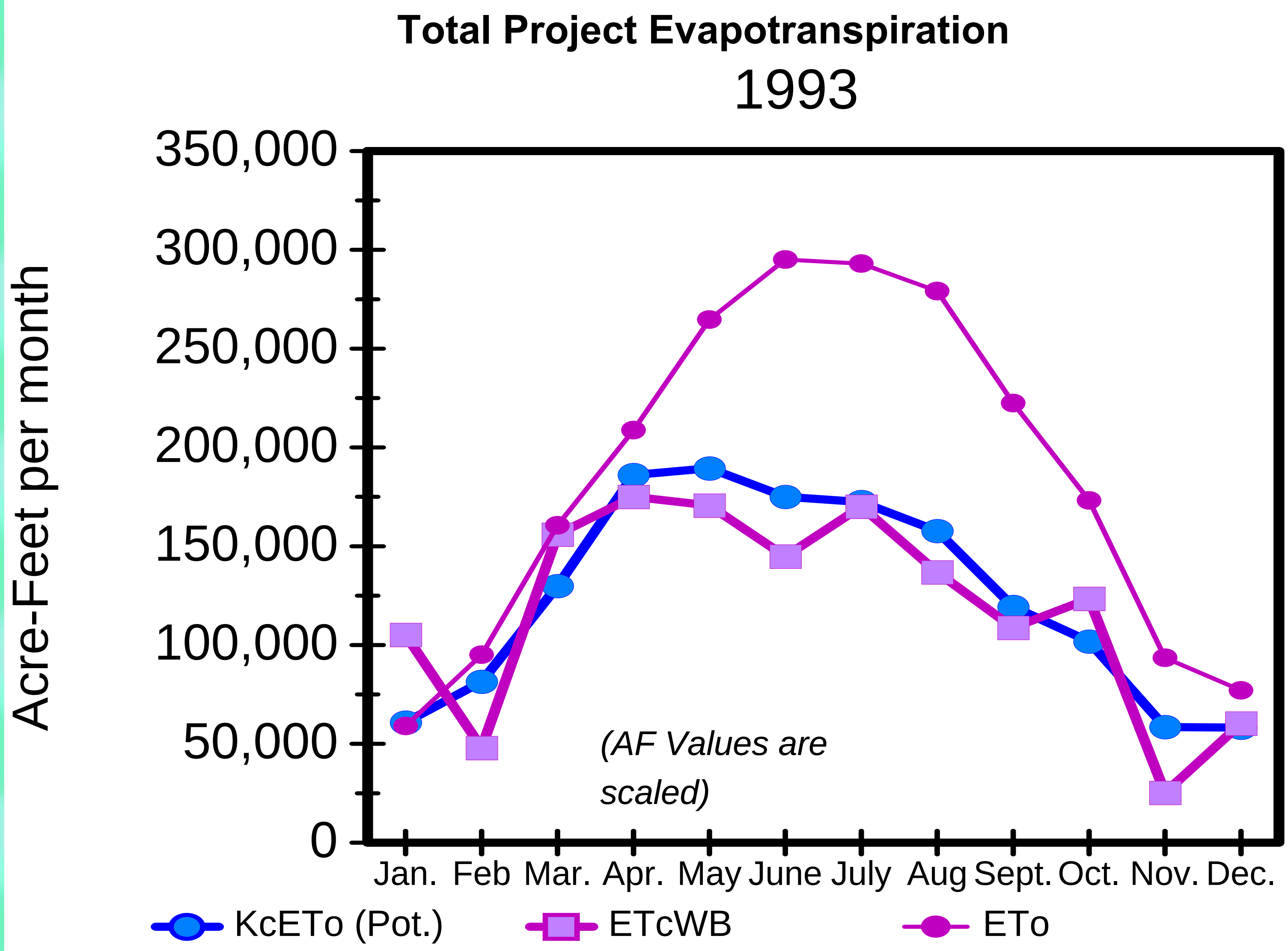




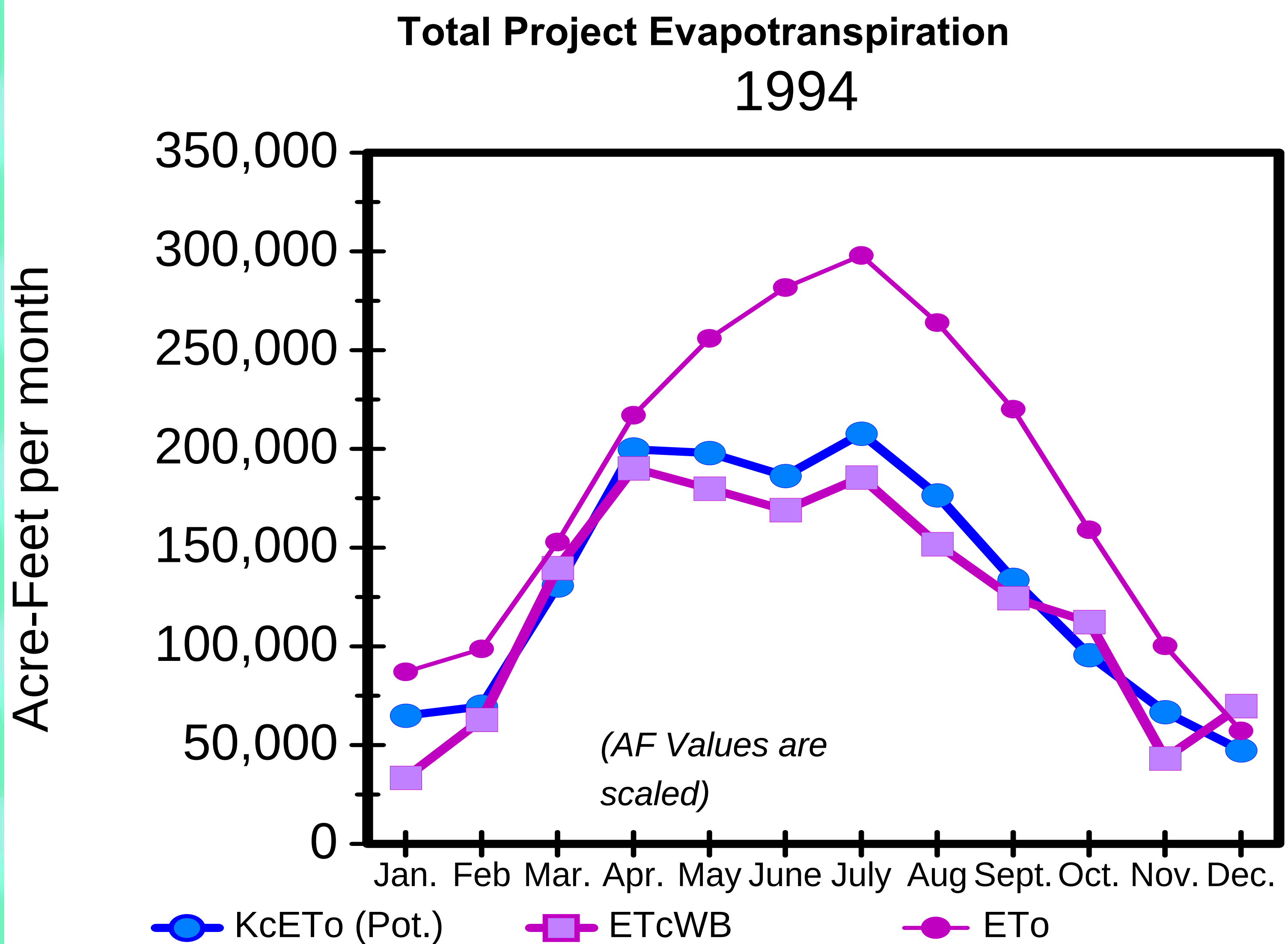
Total Project Evapotranspiration
1991
Acre-Feet per month
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
(AF Values are scaled)
Jan.
Feb
Mar.
Apr.
May
June
July
Aug
Sept.
Oct.
Nov.
Dec.
KcETo (Pot.)
ETcWB
ETo

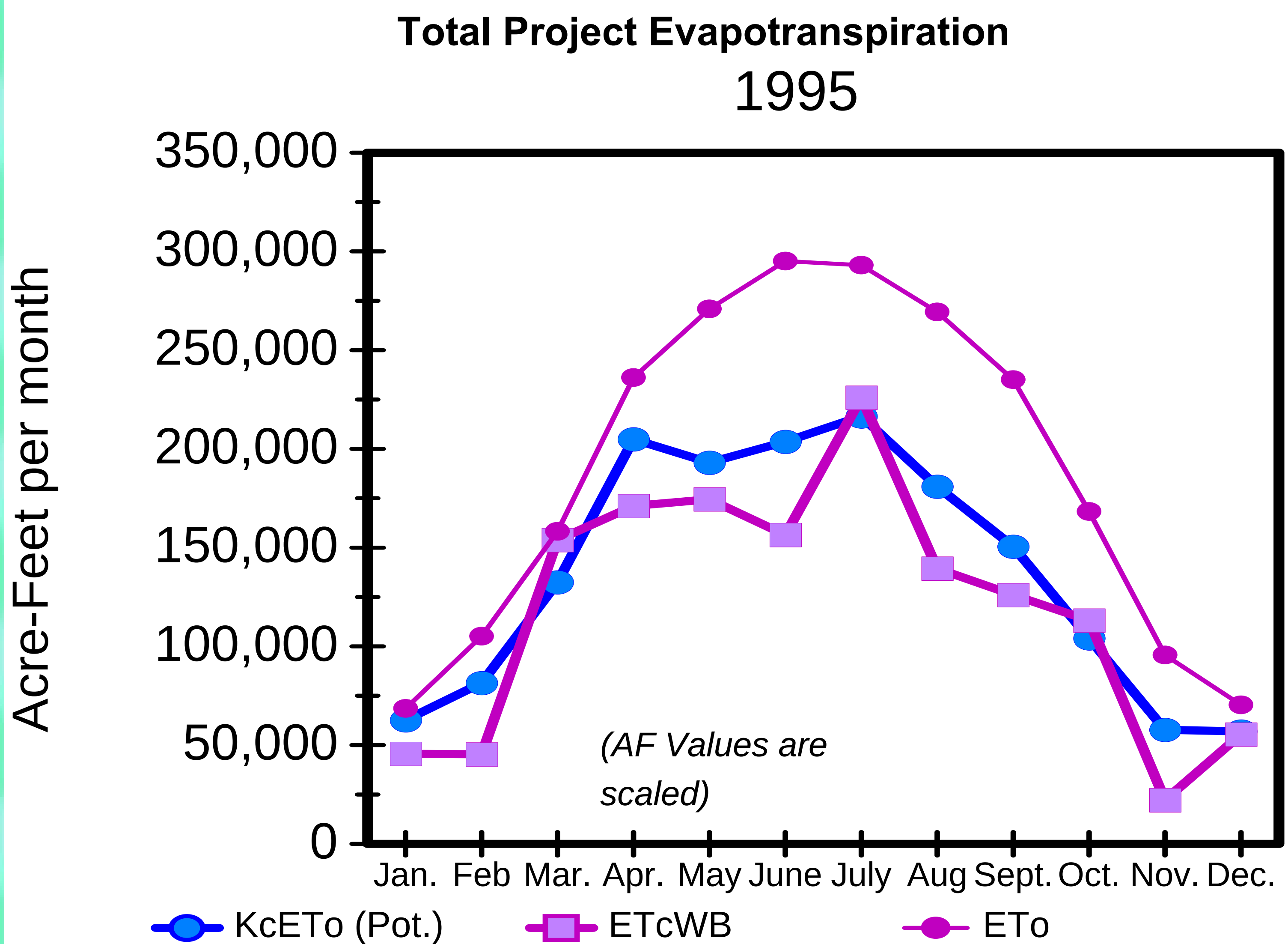


Total Project Evapotranspiration
1992
Acre-Feet per month
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
(AF Values are scaled)
Jan. Feb Mar. Apr. May June July Aug Sept. Oct. Nov. Dec.
KcETo (Pot.)
ETcWB
ETo

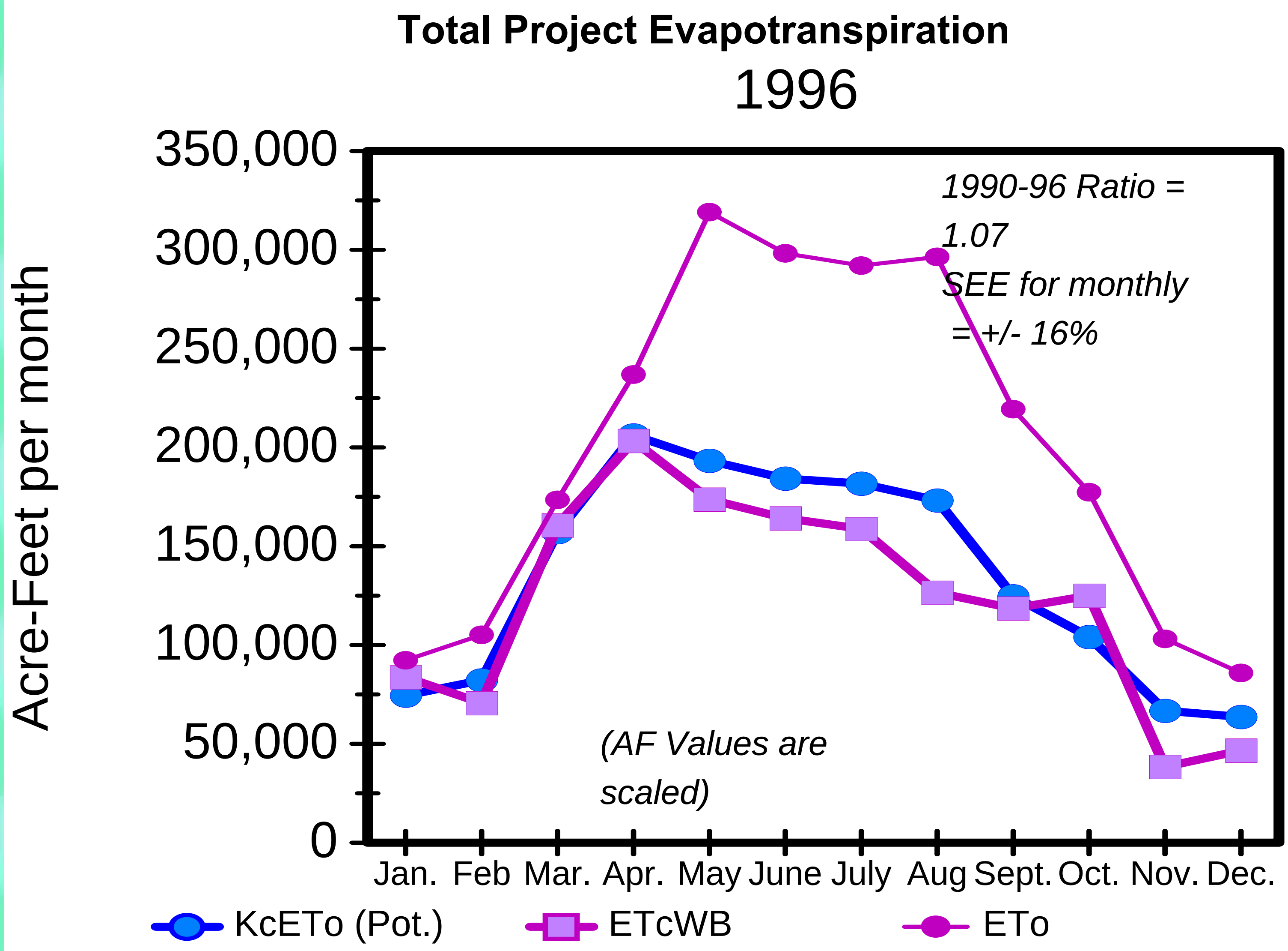


Total Project Evapotranspiration
1993
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
Acre-Feet per month
(AF Values are scaled)
Jan.
Feb
Mar.
Apr.
May
June
July
Aug
Sept.
Oct.
Nov.
Dec.
KcETo (Pot.)
ETcWB
ETo


Total Project Evapotranspiration
1994
Acre-Feet per month
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
Jan.
Feb
Mar.
Apr.
May
June
July
Aug
Sept.
Oct.
Nov.
Dec.
(AF Values are scaled)
KcETo (Pot.)
ETcWB
ETo



Total Project Evapotranspiration
1995
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
Acre-Feet per month
(AF Values are scaled)
Jan.
Feb
Mar.
Apr.
May
June
July
Aug
Sept.
Oct.
Nov.
Dec.
KcETo (Pot.)
ETcWB
ETo



Total Project Evapotranspiration
1996
Acre-Feet per month
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
1990-96 Ratio =
1.07
SEE for monthly
= +/- 16%
(AF Values are
scaled)
Jan.
Feb
Mar.
Apr.
May
June
July
Aug
Sept.
Oct.
Nov.
Dec.
KcETo (Pot.)
ETcWB
ETo

Conclusions

- The K_c ET_r method is robust and transferable
- The K_c incorporates a number of factors affecting ET
- K_c curves can be tailored based on
  - weather data
  - fraction of ground cover
- The dual K_c provides better estimation of impacts of evaporation from soil

Recommendations

- **Don't Believe every K_c you see**
  - **Scrutinize**
    - **measurement technique**
    - **measurement care**
    - **representativeness of plants measured**
      - **same density? same treatment? good health?**
    - **QA/QC on measurement data, weather, ET_r**
  - **Transfer a great distance something good, no distance something poor.**
  - *(Even your mother advised you to date the nice, proper girl (boy) living miles away rather than the rough, biased girl (boy) across the street.)*